

Fuel Design Approach for Low Emission Spray Combustion Fields

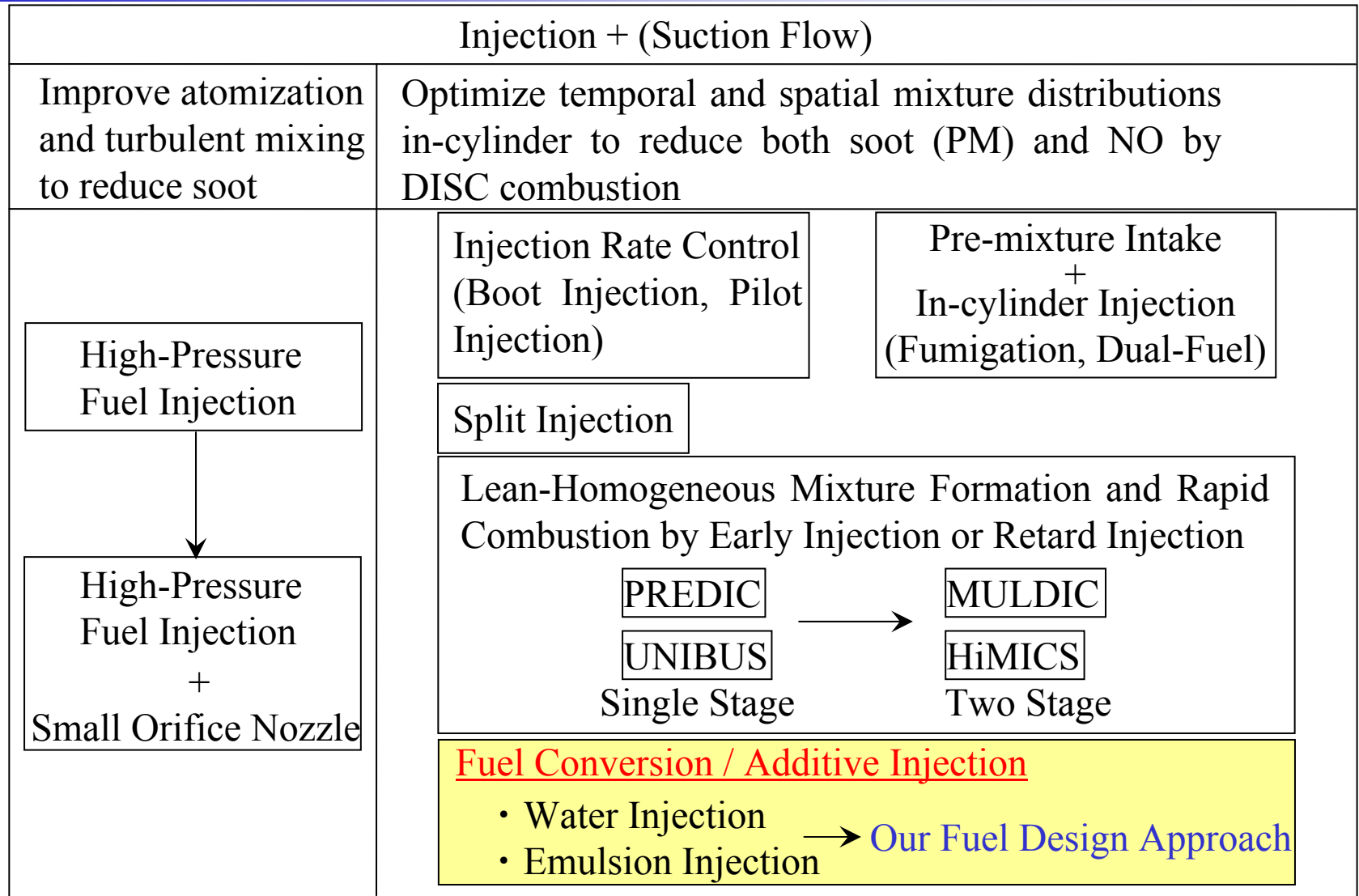
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Contents

- I **Background – Recent Research Trend (HCCI etc.)**
- II **Borderless in Gasoline Eng. and Diesel Eng.**
- III **Proposal of Fuel Design Approach for Both Engines**
- IV **Author's Fuel Design Approach Researches**
- V **Future Extending Research Aspect**



I - BACKGROUND - New Attempts in Diesel Fuel Injection System for Exhaust Emission Reduction



II - Borderless in Gasoline Eng. & Diesel Eng.

Gasoline Engine

Mixture formation

In recent gasoline engines & diesel engines...

- Mixture formation
- Combustion mode

No definite boundary

Heterogeneous
diffusion combustion

homogeneous
premixed combustion

III Proposal of Fuel Design Approach for Both Engines

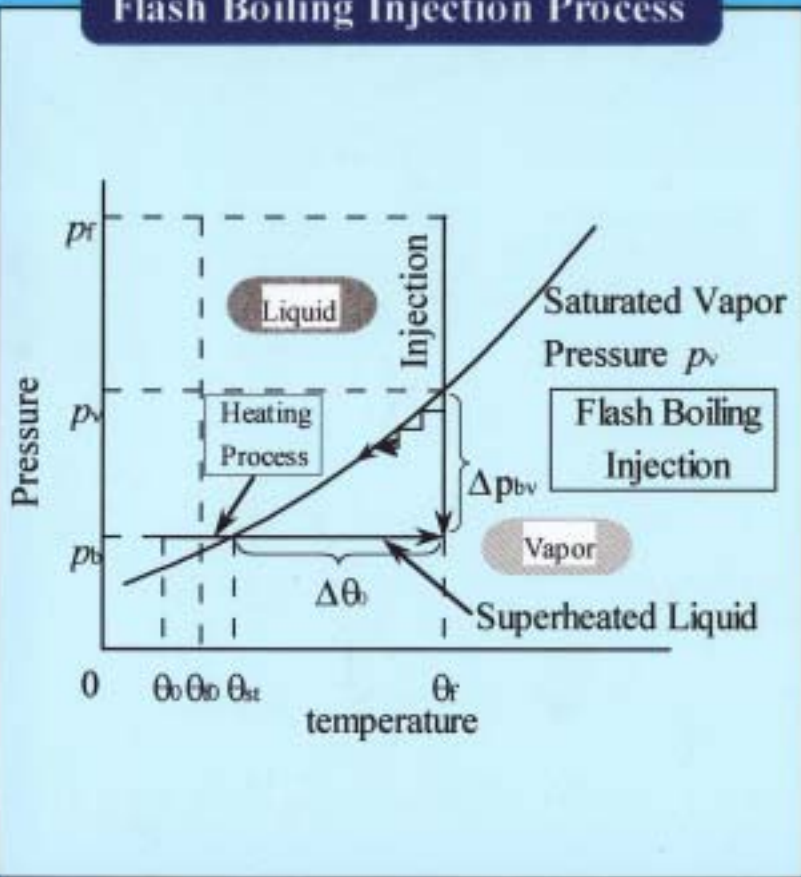
Key technology = Flash Boiling Spray

1. Mixing Fuel with Liquefied CO₂
2. Mixing Fuel with High and Low Volatility Fuels
3. Soot Free Combustion with
Oxygenated fuels from kinetic analysis

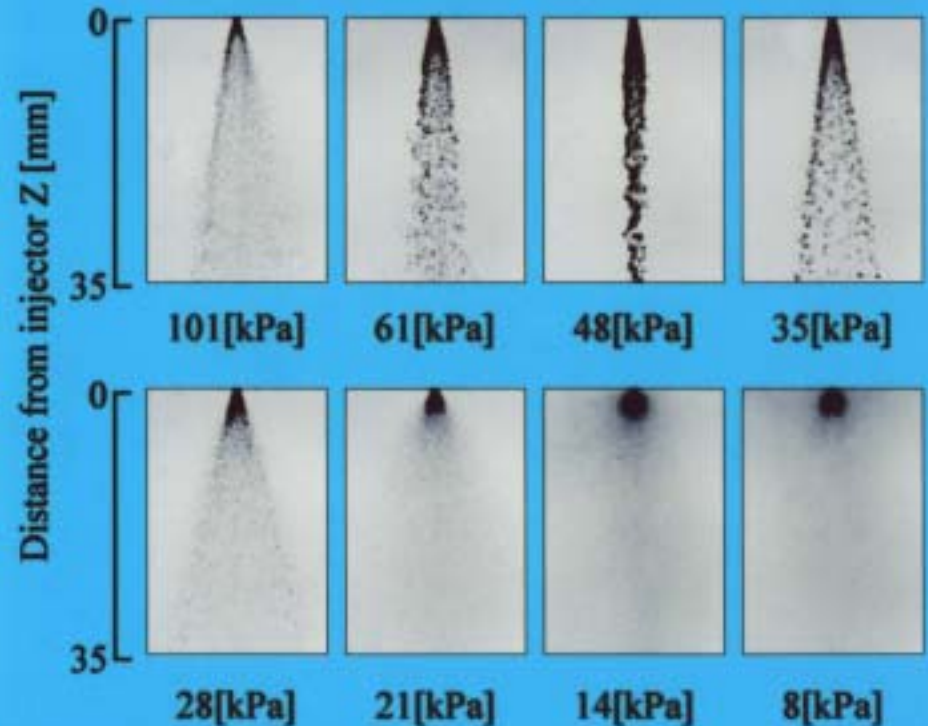
What is Flash Boiling Spray ?

Improvement of Spray Atomization by Flash Boiling

Flash Boiling Injection Process



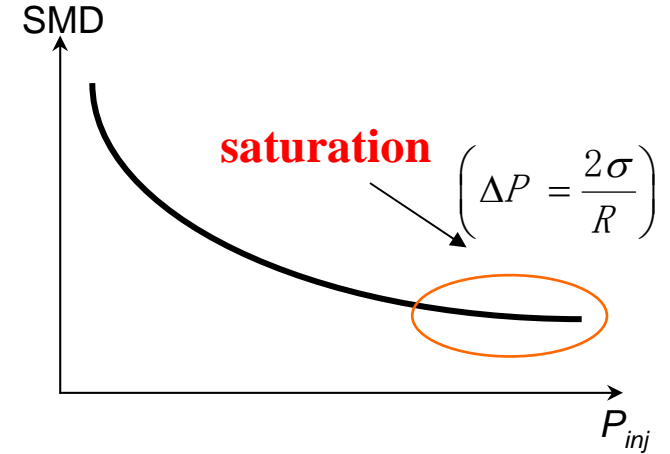
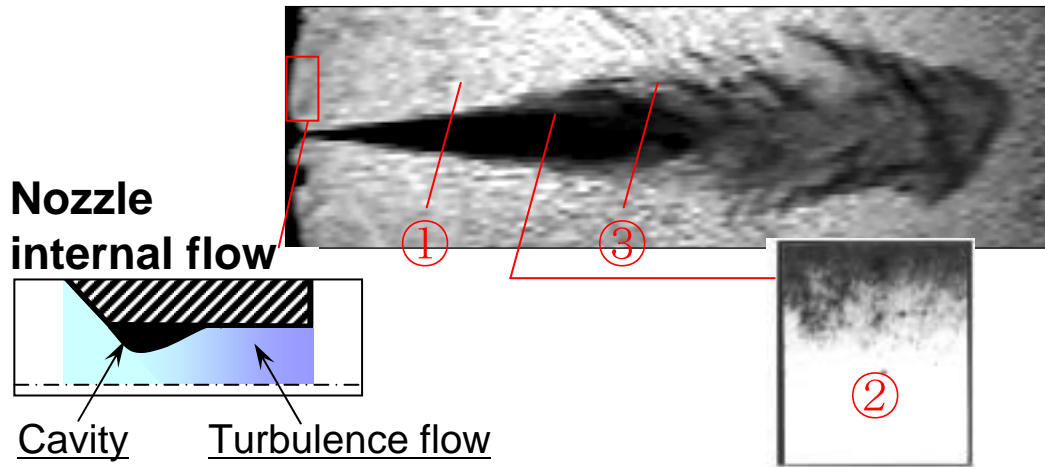
Flashing Spray of n-Pentane ($P_v = 56.5$ KPa)



Atomization & Evaporation in Pressure atomizer

→ Time & Spatial delay depending on P_{inj} , ρ_a , T_a

Aerodynamical Process : disturbance ⇒ ligament ⇒ droplets

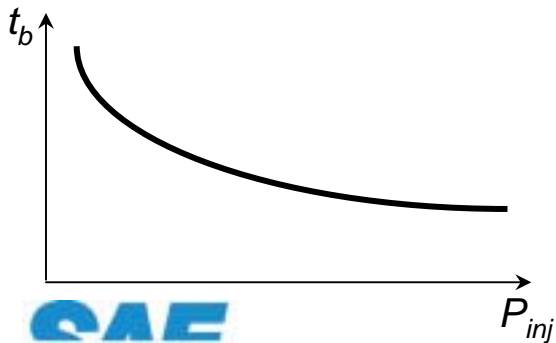


① Breakup delay of spray

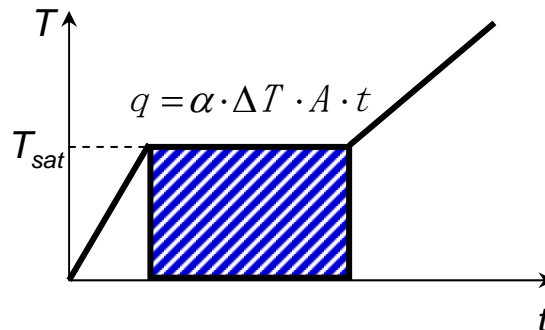
② Evaporation of droplets

③ Evaporation length of spray

$$t_b = 28.65 \frac{\rho_l \cdot d_0}{\sqrt{\rho_a \cdot (P_{inj} - P_a)}}$$

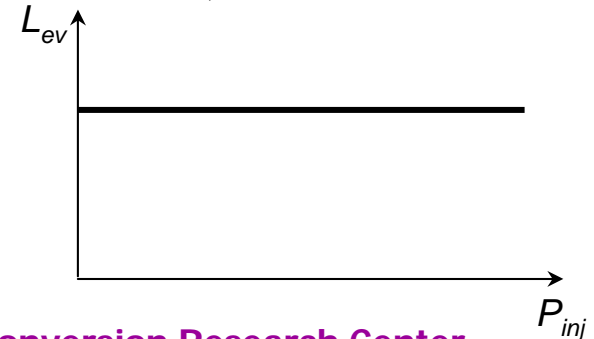


$$Nu = c \cdot Re^\alpha \cdot Pr^\beta \rightarrow Nu = 2$$



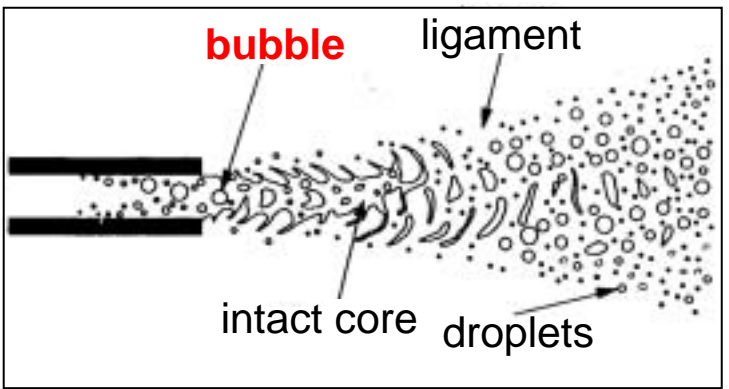
$$\dot{m}_f \propto \rho_f \cdot d_2 \cdot U_f$$

$$\dot{m}_a \propto \sqrt{\rho_a \cdot \rho_f} \cdot d \cdot x \cdot U_f \cdot \tan(\theta/2)$$



Atomization & Evaporation in Flash Boiling Spray

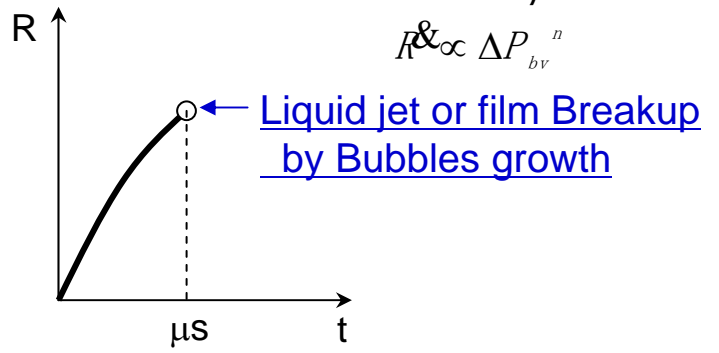
→ Non Time & Spatial delay depending on Two Phase profile($\Delta P_{bv}(\Delta\theta)$)



Bubble Nucleation rate $N \propto C \cdot \exp\left(-\frac{\Delta A}{k\Delta\theta}\right)$
 $\Delta A = \frac{4}{3}\pi R^2 \cdot \sigma$

Evaporation rate = Bubble growth Rate

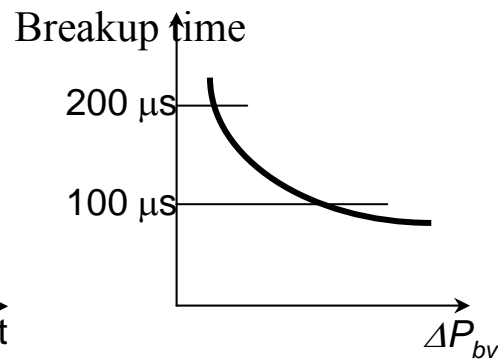
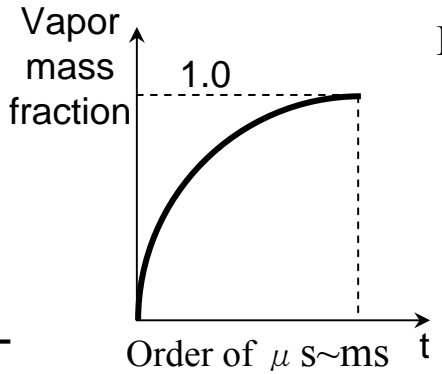
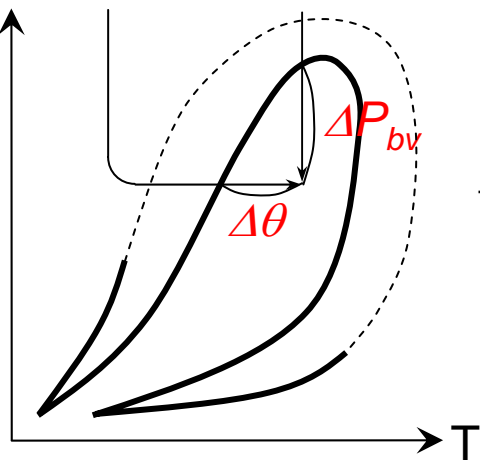
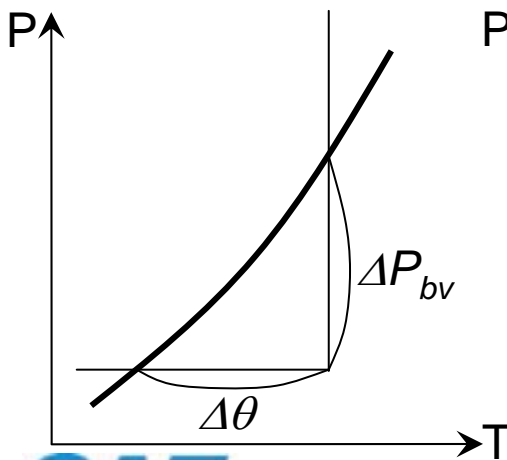
Rayleigh-Plesset Eq. $R\frac{dR}{dt} + \frac{3}{2}R^2\frac{dR}{dt} = \frac{1}{\rho}(P_w - P_r)$
 $R \propto \Delta P_{bv}^n$



❖ Evaporation due to Enthalpy balance of fuels without aerodynamic force

Single Component

Multi-Component



Proposal on Fuel Design Approach Research

- (1) Physical Control = Capability of Time and Spatial Control on Fuel Vapor Distribution by Formation of Two Phase region in Mixing Fuel**
→ **Formation of Flash Boiling Spray → Improvement of Spray Evaporation**

- (2) Chemical Control = Capability of Control on Combustion Process**
→ **Emission Control – Soot & NO_x**
 Simultaneous reduction of both Soot and NO_x (CO₂-gas oil mixing fuel)
→ **Ignition Control (Gasoline-gas oil mixing fuel)**
→ **HC Control (Gasoline-gas oil mixing fuel)**

- (3) Improving Thermal Efficiency by Lower Injection Pressure**
→ **High Spray Atomization and Evaporation Quality with Flashing Process**

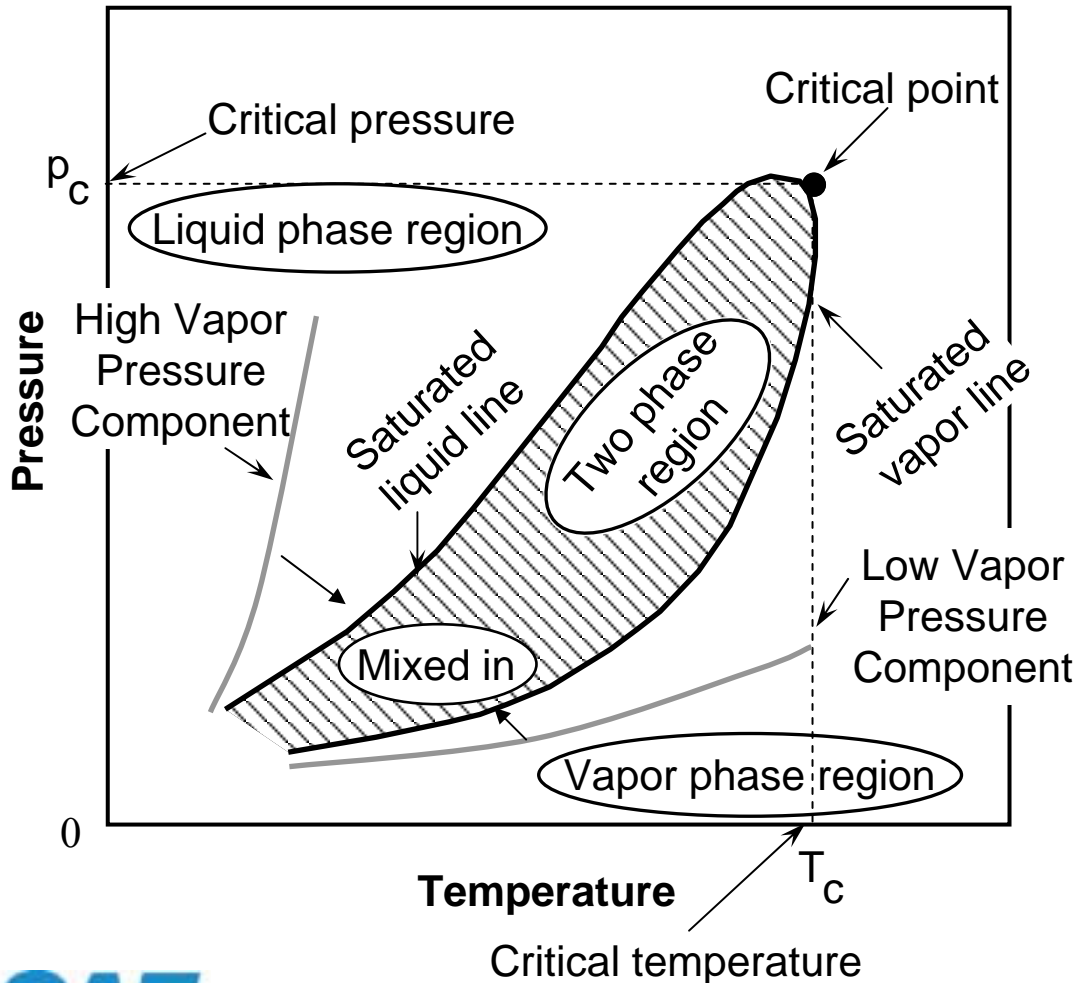
- (4) Control the Fuel Transportation Properties in Mixing Fuels**

- (5) Effective liquefaction of gaseous and solid fuels**
→ **Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics**

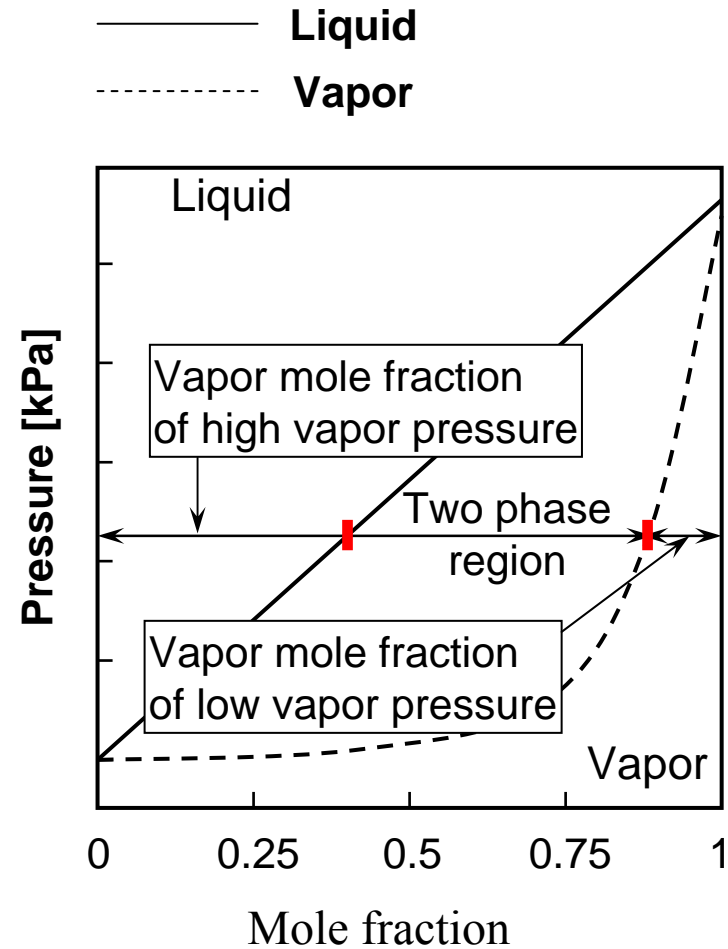


Two Phase Region Formation in Multi-component Fuel in Phase Change Process

Pressure-temperature diagram



Pressure-Mole fraction diagram

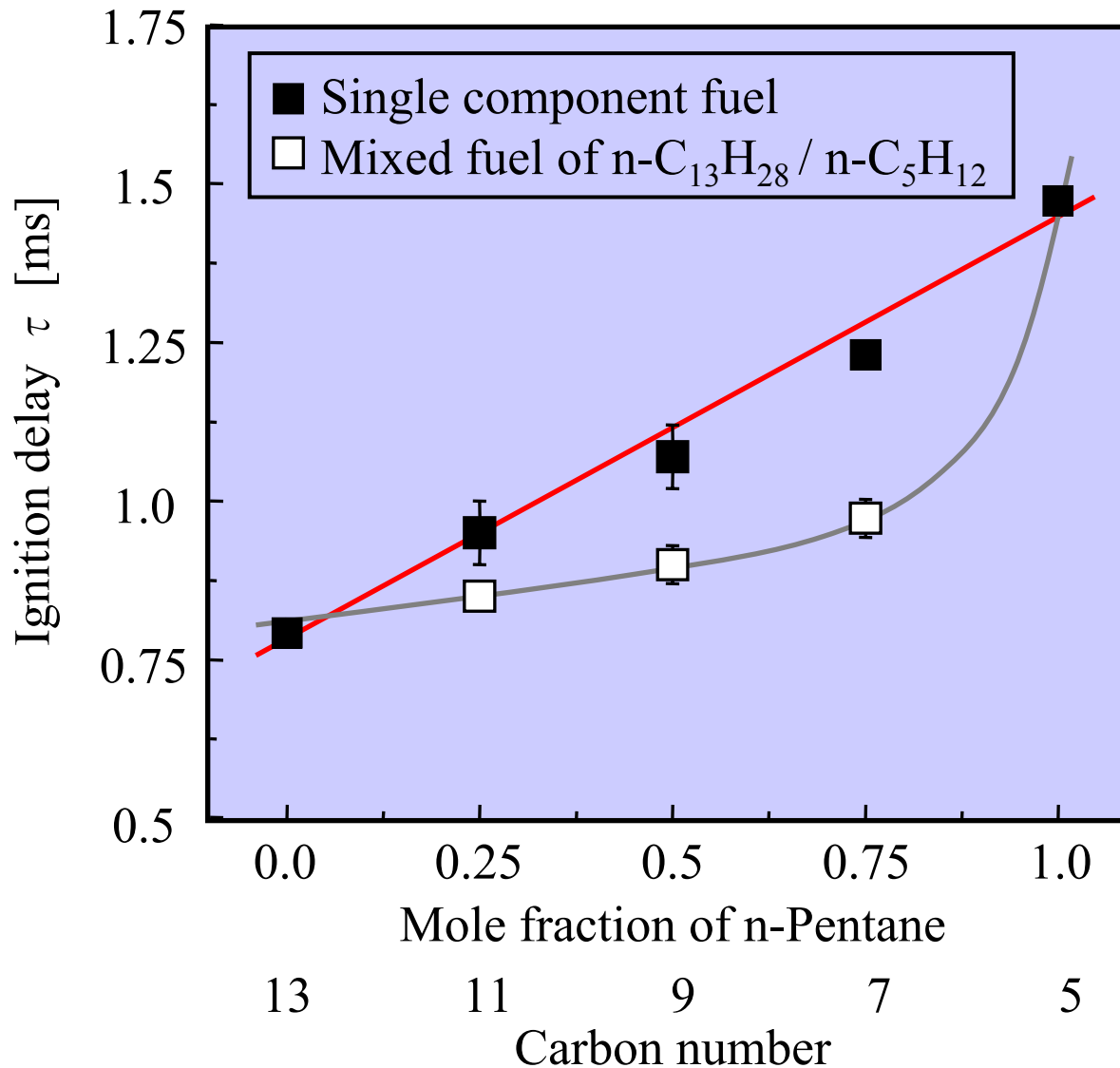


Proposal on Fuel Design Approach Research

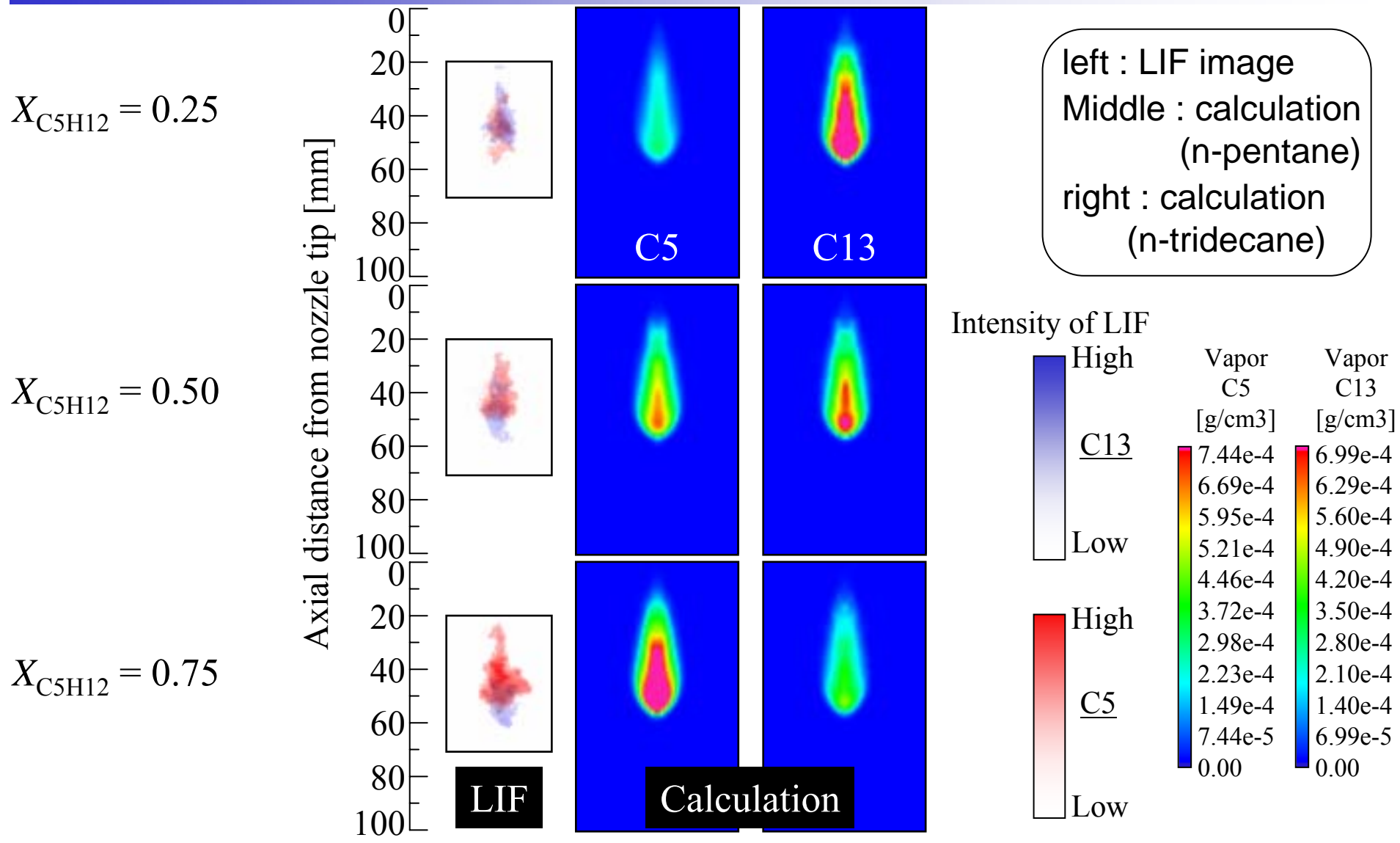
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Ignition delay of mixing fuel of C₅H₁₂ with C₁₃H₂₈ and single component fuel (Experiments)

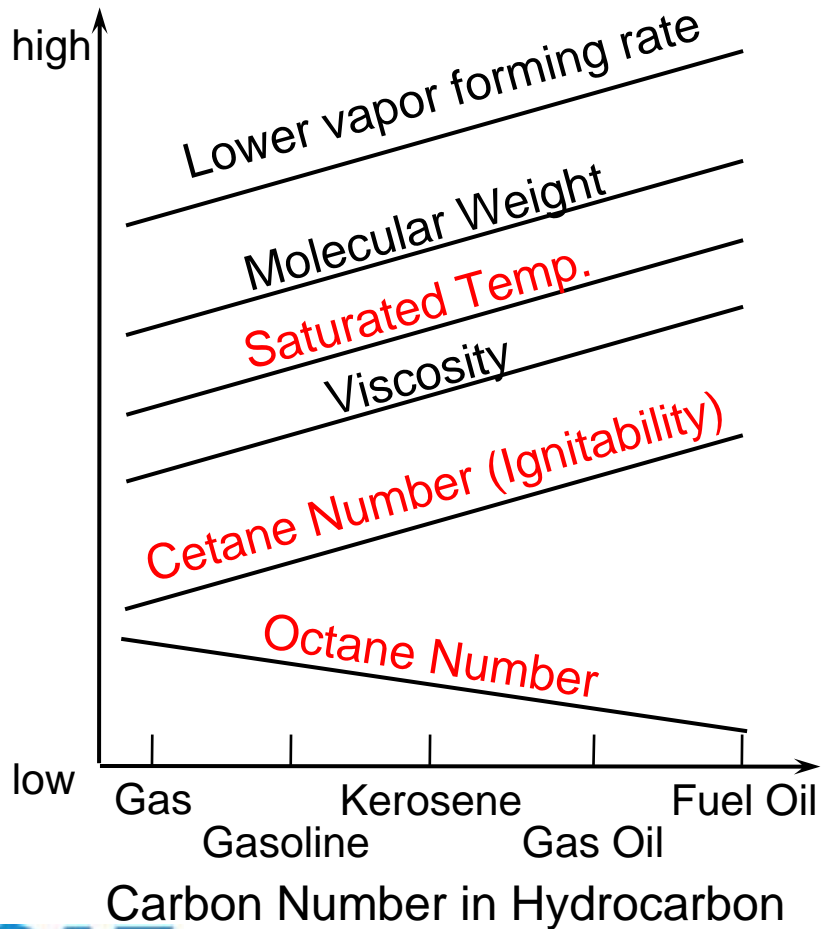


Comparison of Spray Structure –Vapor Spatial Distribution– with Experiments and Numerical Results at $t=3.0\text{ms}$



Multi-component Fuel Spray Behavior in Diesel Combustion Chamber

The chemical & physical properties of n-paraffin Hydrocarbon

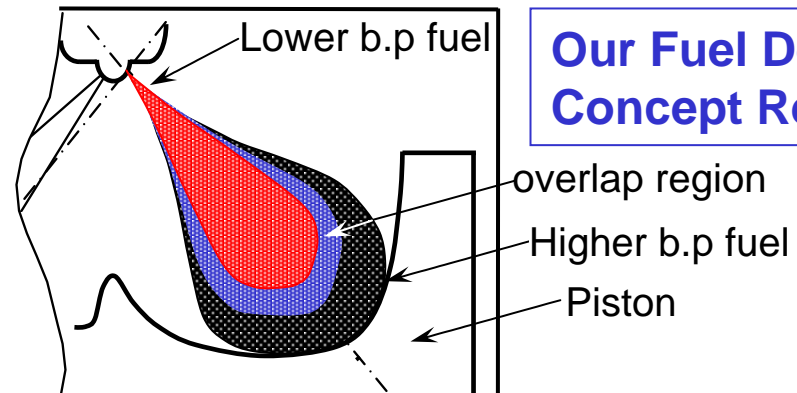


Lower boiling point fuel (gasoline)

- higher evaporation
- higher octane number = poor ignitability

Higher boiling point fuel (gas oil)

- lower evaporation
- higher cetane number = high ignitability



Our Fuel Design Concept Research

- stratified fuel vapor distribution
- ignition at the middle part of the spray
 - balance of physical and chemical
- Disc shaped chamber is selected reasonably through fuel physical and chemical properties

Possibility in coupling of Physical Control and Chemical Control for Spray Combustion

By using the Mixing Fuel of Higher Boiling Point Fuels (gas oil, etc) and Lower Boiling Point Fuels (gas fuel or Gasoline, etc)

1.Lower B.P. fuel could promote the evaporation
through the formation of Two Phase Region

→Spatial overlap vapor distribution in the chamber

2.Higher B.P.fuel could assist the ignition
and **Higher B.P. fuel could burn out the lower ignitability fuel** such as Lower B.P. fuel

(5) Effective liquefaction of gaseous and solid fuels

1. Possible application for Gas Fueled Engines and Transportation

Liquefied Pressure of Gas Fuels can be reduced by mixing the higher boiling point fuel through the Two Phase Region (It means saturated vapor pressure is reduced)

→ Safety of compressed gas bomb or liquefied gas bomb

→ Longer driving distance in CNG or LNG engine transportation

2. As a Future study

Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics with assisting by Sono-Chemistry Process

→ Effective usage of fossil energy resources



IV Author's Fuel Design Approach Researches

- ① **Mixing Fuel of Liquefied CO₂ and n-Tridecane(gas oil)**
→ simultaneous reduction both Soot and NO_x

- ② **Mixing Fuel of Gas or Gasoline Component and Gas oil Component** → to control both evaporation and ignition

Scenario of Low Emission Diesel Combustion by Mixing Fuel Injection of Liquid CO₂ & n-Tridecane (gas oil)

Concept

1. Low injection pressure

→ to improve efficiency

2. Improvement of spray atomization & Formation of vaporizing spray

→ to form lean & homogeneous mixture

3. Control of combustion processes

→ to reduce both NO and soot

Low Emission Scenario

NO reduction

Lower Flame Temperature by

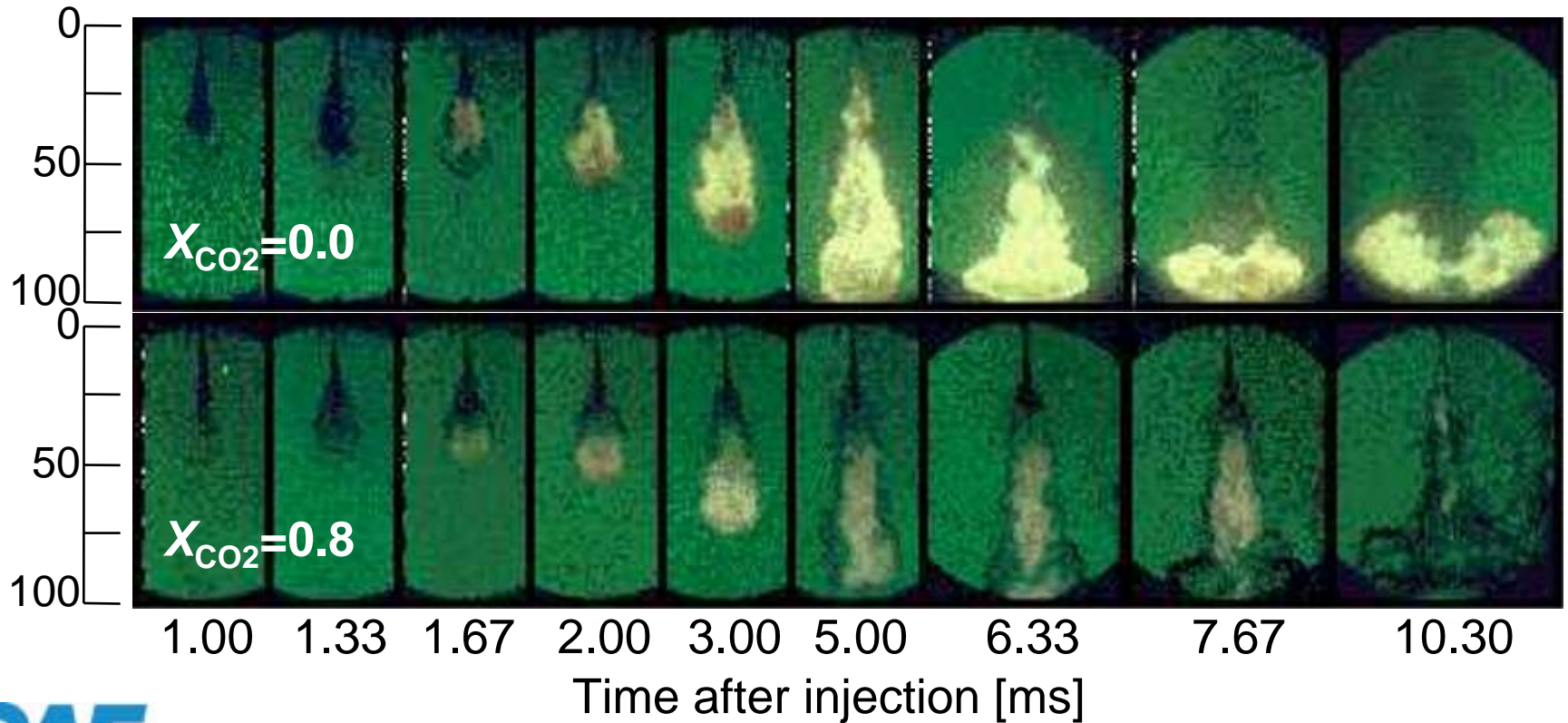
- (1) Latent heat of CO₂ flashing
- (2) Thermal dissociation of CO₂
($2\text{CO}_2 \Rightarrow 2\text{CO} + \text{O}_2$)
- (3) Improvement of spray atomization and vaporization due to CO₂ separation and flashing

Soot reduction

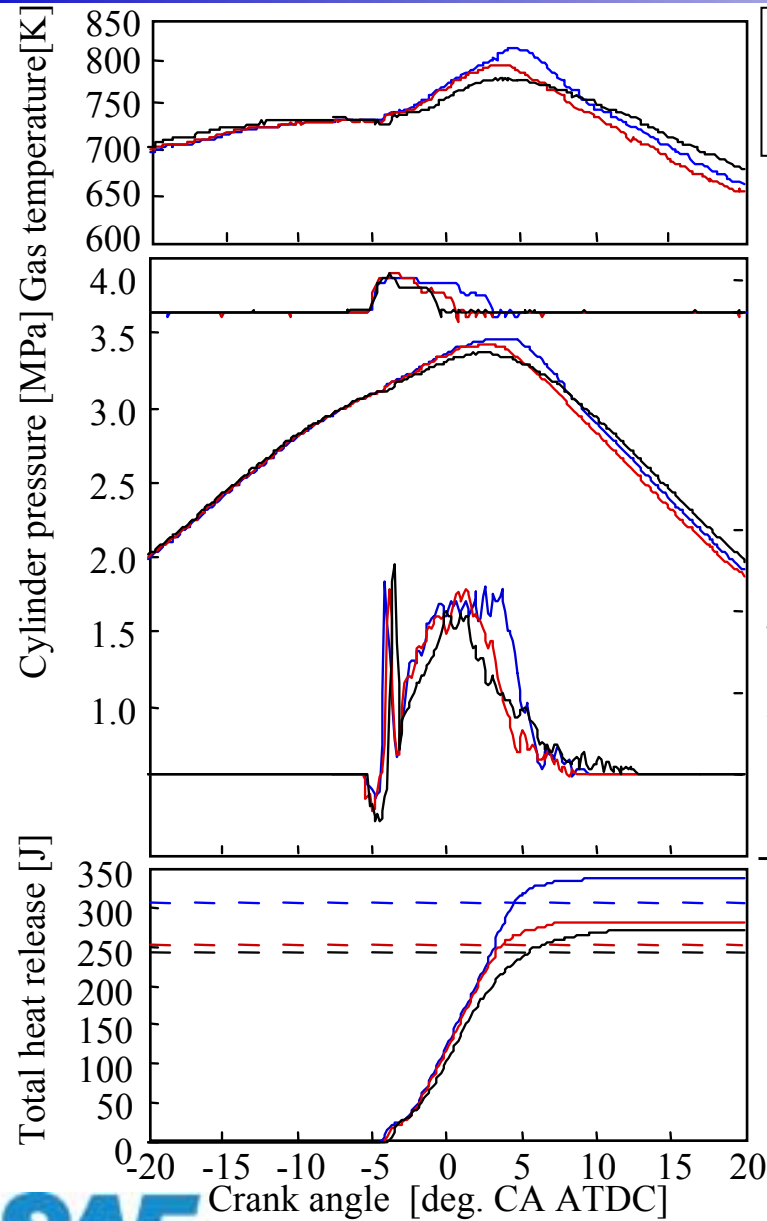
- (1) Soot formation
 - avoid the fuel rich mixture
- (2) Soot oxidation & re-burning
 - Dissociation of CO₂ into CO and O
 - Boudouard reaction $\text{C} + \text{CO}_2 \Rightarrow 2\text{CO}$

Combustion Characteristics of CO₂/C₁₃ Mixing Fuel

- Low pressure injection → Improve the Thermal Efficiency
- Flash boiling spray by CO₂ component → Promotion of Spray Evaporation
- Spray internal EGR → Reduction of NO_x

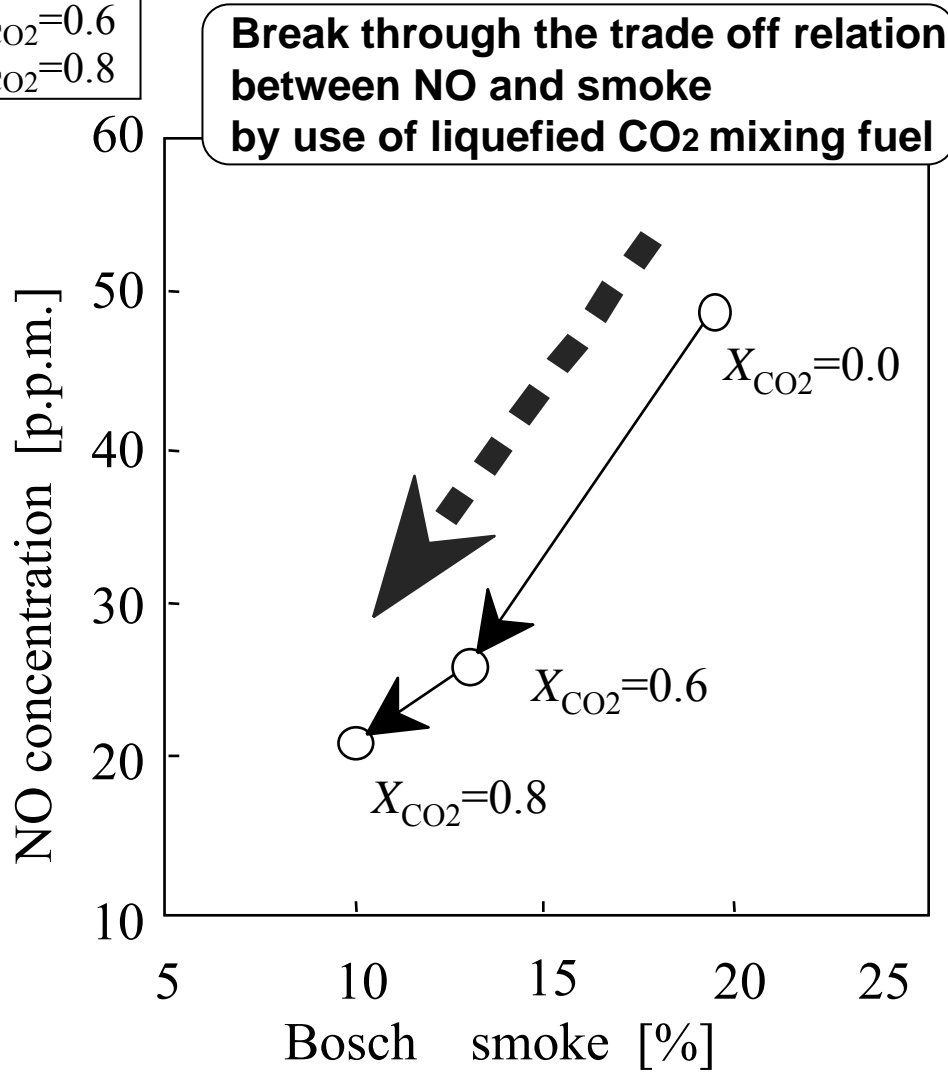


Combustion Characteristics of CO₂/C₁₃ Mixing Fuel

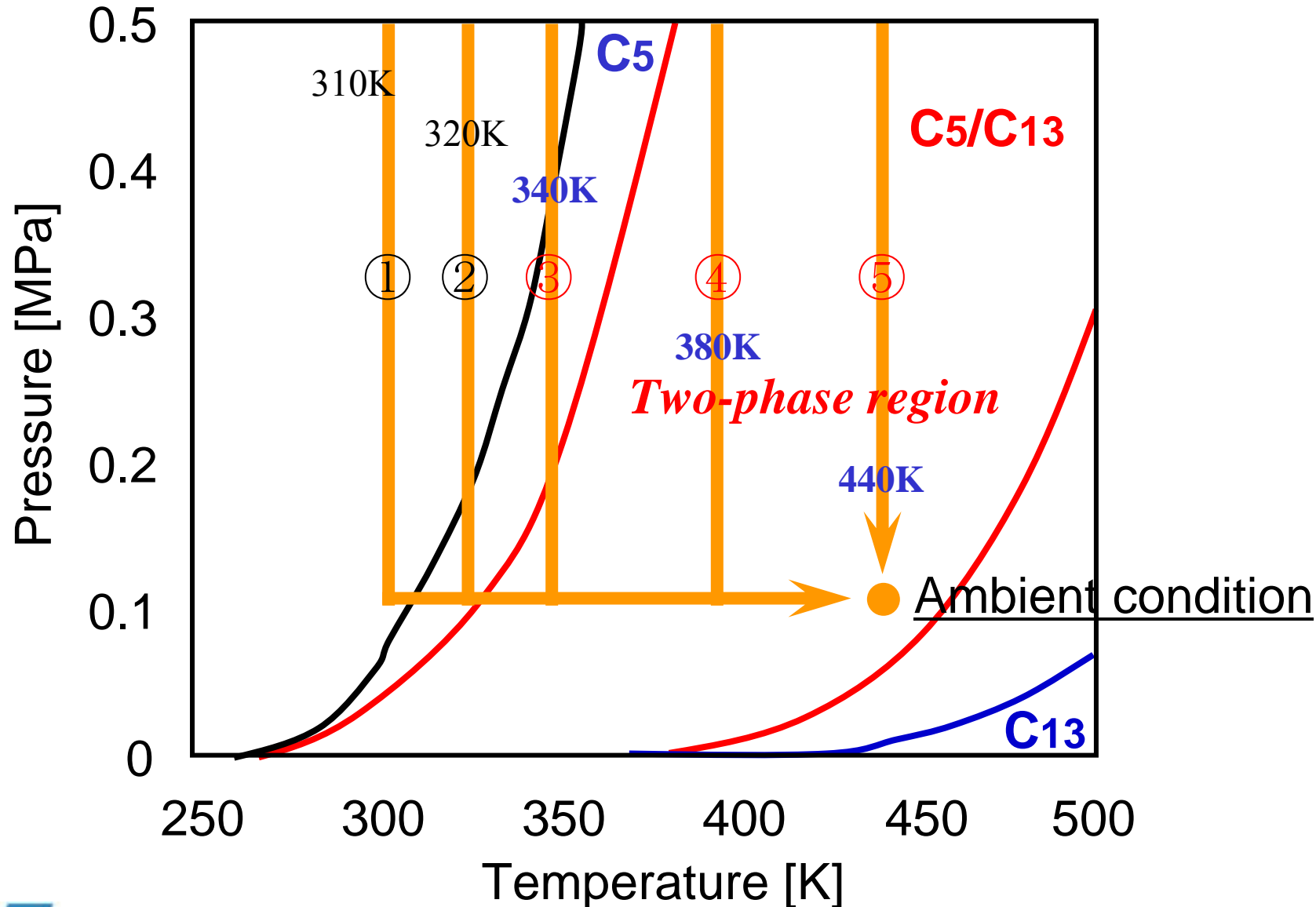


— $X_{CO_2}=0.0$
 — $X_{CO_2}=0.6$
 — $X_{CO_2}=0.8$

Needle lift
 Rate of heat release [J/deg.]



Experimental Conditions for Heated up Mixing Spray

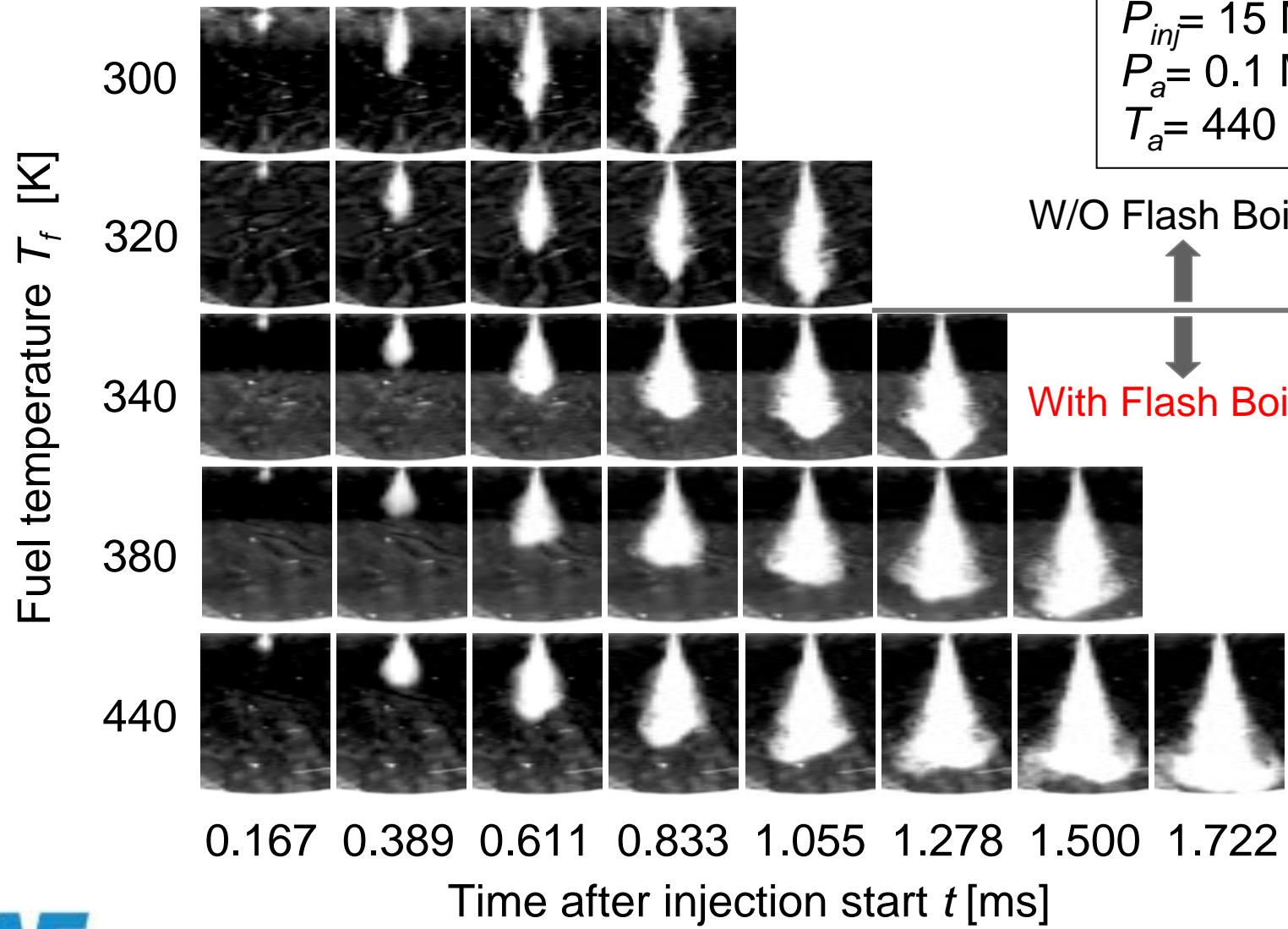


Shadowgraph Images of Flashing Spray of C5/C13 Fuels

$r_a = 0.765 \text{ kg/m}^3$
 $P_{inj} = 15 \text{ MPa}$
 $P_a = 0.1 \text{ MPa}$
 $T_a = 440 \text{ K}$

W/O Flash Boiling

With Flash Boiling



Combustion Experimental Conditions and Emission Results in C5 & C13 Mixing Fuel

Test fuel

$n\text{-C}_5\text{H}_{12} + n\text{-C}_{13}\text{H}_{28}$ (C5/C13) $X_{\text{C}_5\text{H}_{12}} = 0.0, 0.25, 0.50, 0.75$

Operating condition

Engine speed [rpm] 3600

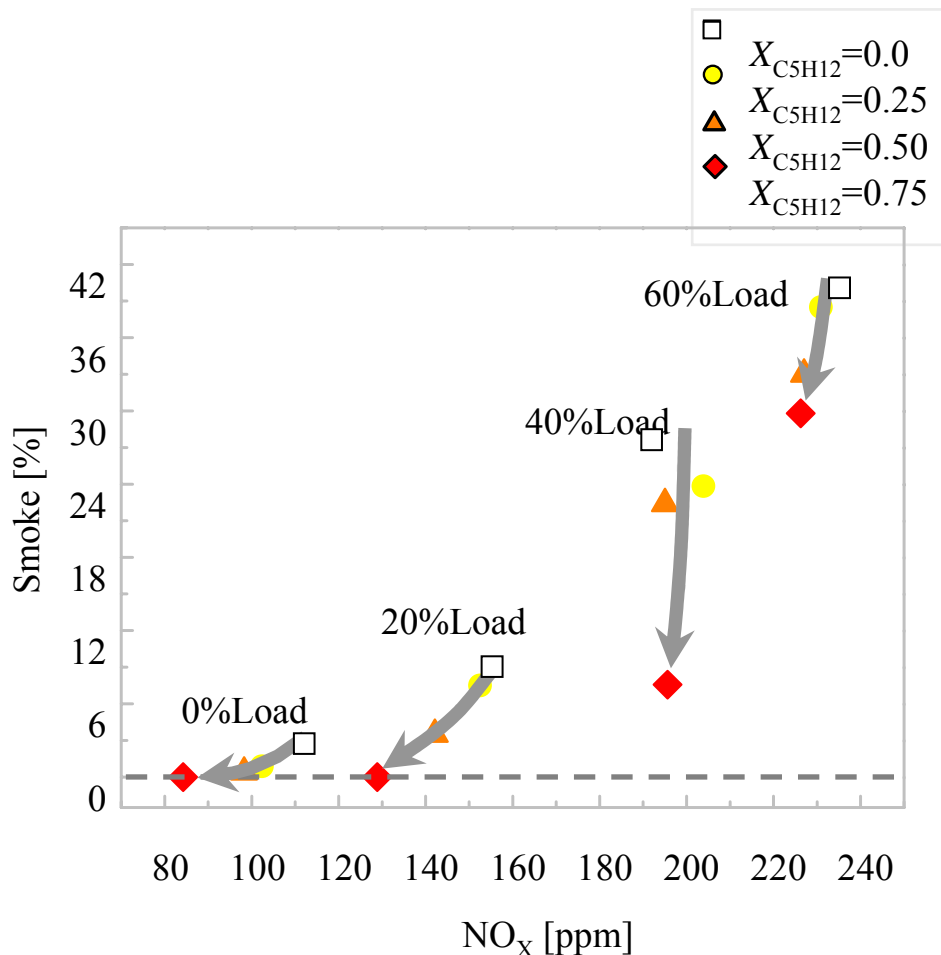
Engine load [%] 0, 20, 40, 60

Injection condition

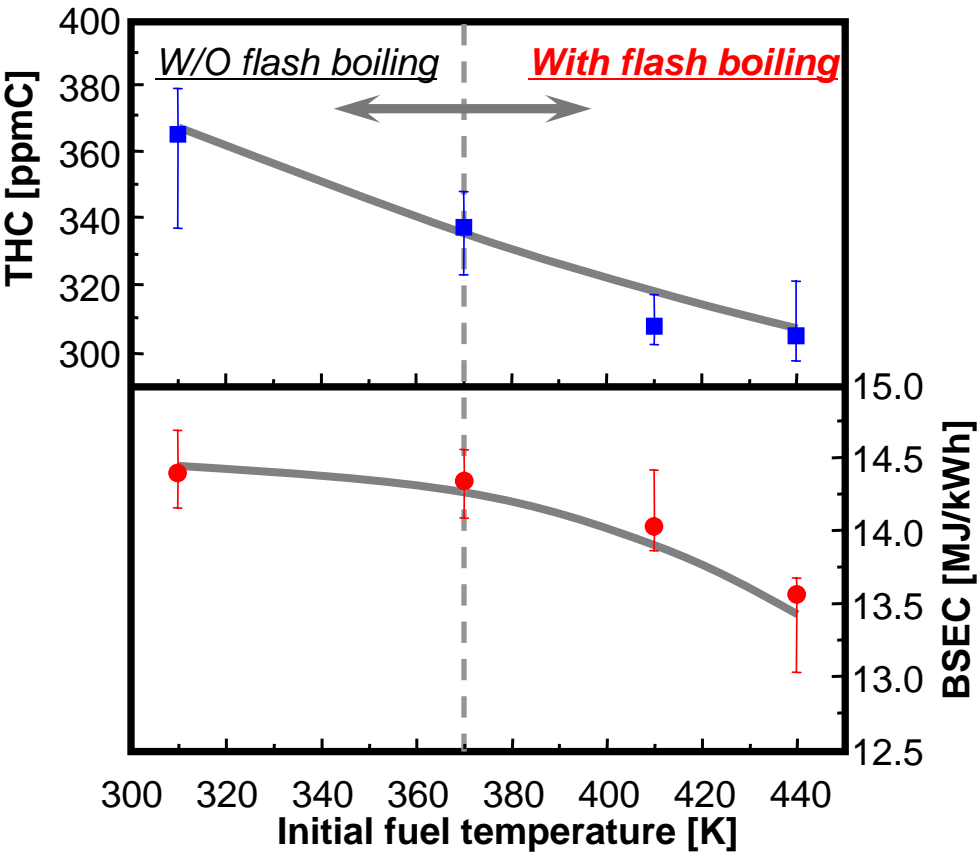
Injection nozzle ($n\text{-}\phi$ d) 4- ϕ 0.21

Injection pressure [MPa] 15MPa

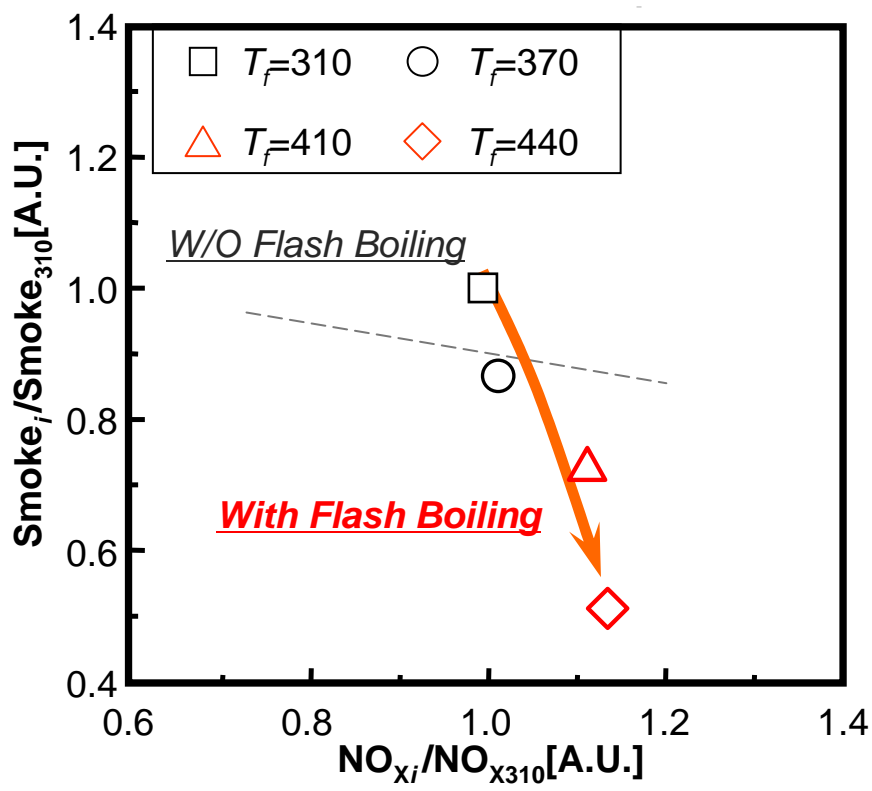
Injection timing [deg.C.A.BTDC] 12



Emissions and Engine Performance (Mixing of LPG/C13)



(a) THC Emission and Engine Performance



(b) Relation between Smoke and NO_x



V Future Extending Research Aspect

- 1. Application of Fuel Design Approach into HCCI engines for Lower Emissions and Ignition Control**
- 2. Coupling of Fuel Design Approach with Combustion Chamber Geometry Design**

HCCI Application of Fuel Design Approach

< HCCI Engines >

- **Advanced fuel Injection → Lower Ta & Pb**
- **Ignition control is required → Ignition improver
Some additives**
- **Importance in Spatial Vapor Distribution
→ Homogeneity or Heterogeneity ?**

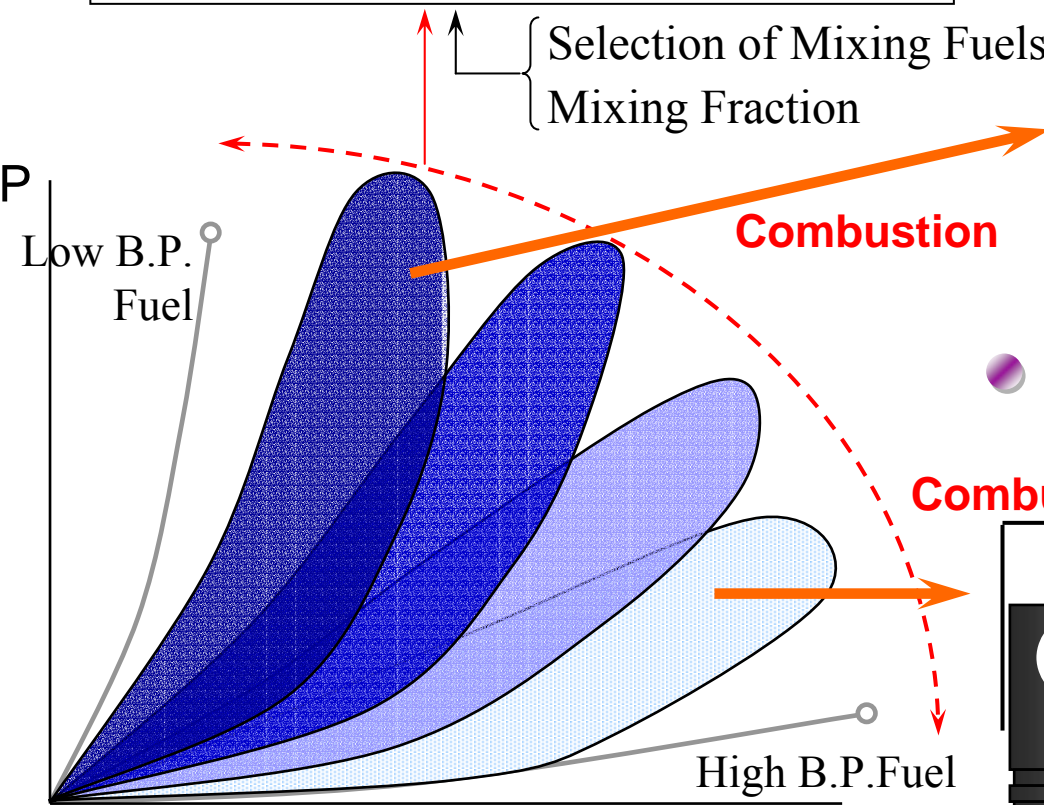
< Fitting of Mixing Fuels to HCCI >

- * **Possibility of Flashing Spray due to lower Ta & Pb**
- * **Mixing Additives can control the Ignition Process**
- * **Controllability of Spatial Vapor Distribution
due to the Two Phase Region Profile**

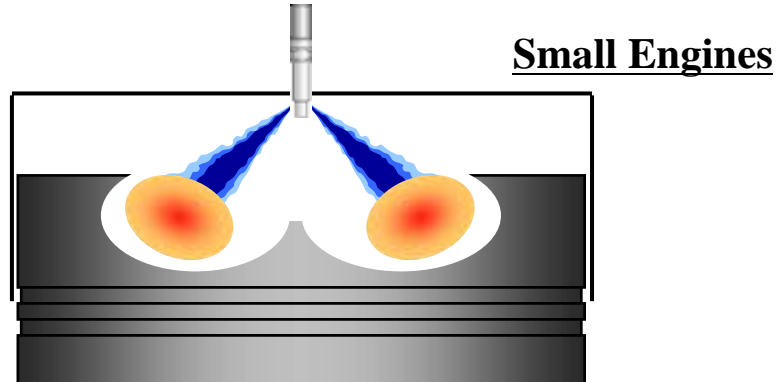
Optimization of Spray Evaporation Process and Chamber Geometry by adjusting Two Phase Profile of the Fuel

- Spray should be penetrated to near the chamber wall where air mass is enough
- HC and PM should be reduced by avoiding the spray and wall interaction

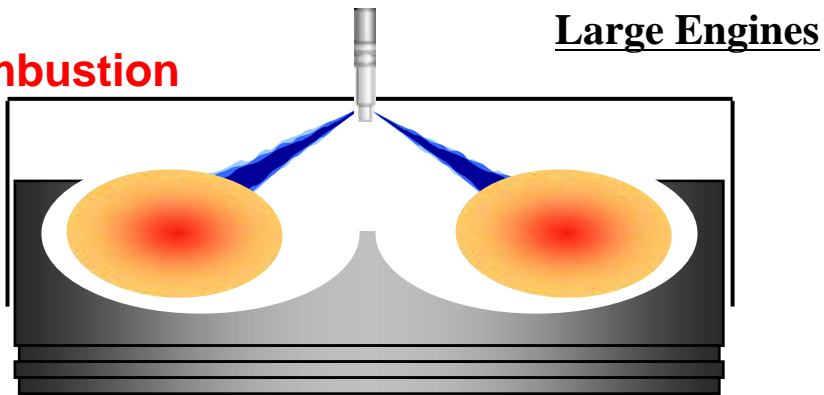
Optimization of Two Phase Region Profile



● Formation of Shorter Spray



● Formation of Longer Spray



The END - 完 -

My standpoint is that ;

1. In-Cylinder ultimate NOx & PM reduction can reduce the catalyst load
2. For both engines, simultaneous reduction of NOx and PM should be required with reducing CO2 (with improving the efficiency)
3. It might be better that PM is reduced up to the limitation level inside the cylinder through spray –combustion improvement with fuel research. And NOx is reduced with NOx catalyst (Urea-SCR, LNT,DPNR)

Thank you for your kind attention

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I Background – Recent Research Trend

- Introduction of Several HCCI Approaches
- Possibility of HCCI Application into Diesel Engines in High Load Operation

Development in DI HCCI (1995 ~)

MK (NISSAN)

- with high swirl, high EGR and retarded injection timing

UNIBUS (TOYOTA)

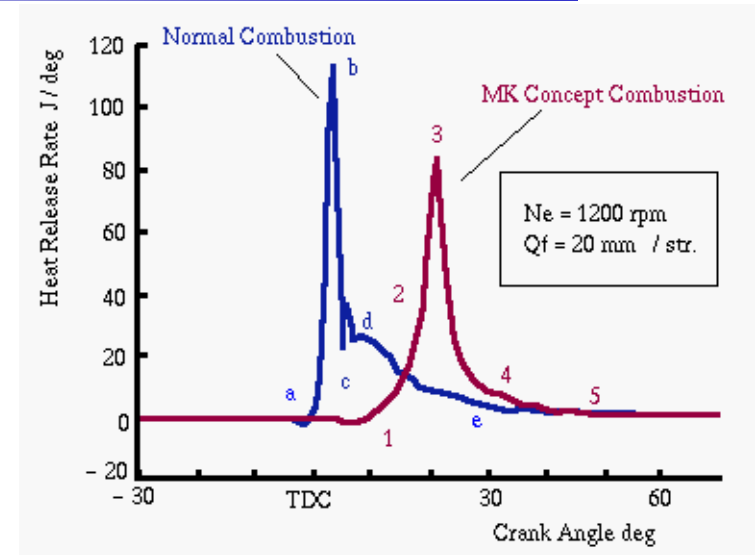
- with dividing fuel injection into two stages in order to enable rapid combustion at low temperatures

HiMICS (HINO)

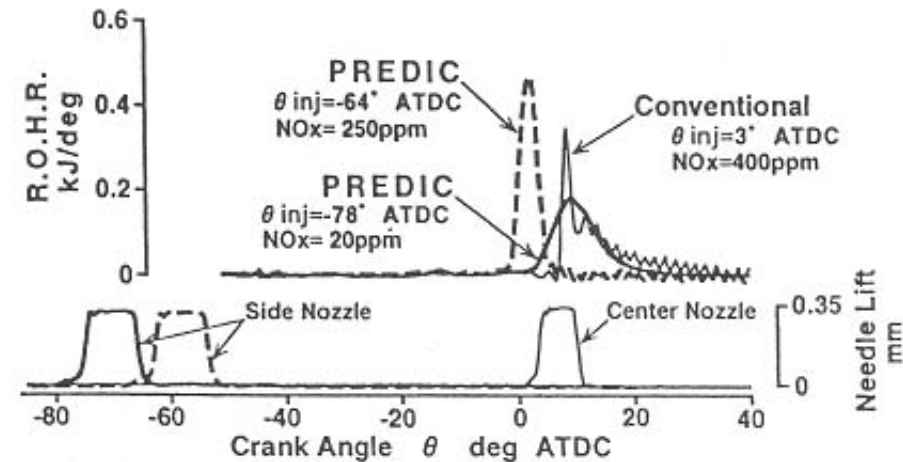
- with multiple injection system
(early stage inj., pilot inj.,
main inj., late stage inj.)

PREDIC (New ACE)

- with two side injectors in order to avoid collision of the spray with cylinder wall



[Ref: SAE Paper 1999-01-3681](#)



[Ref: SAE Paper 961163](#)

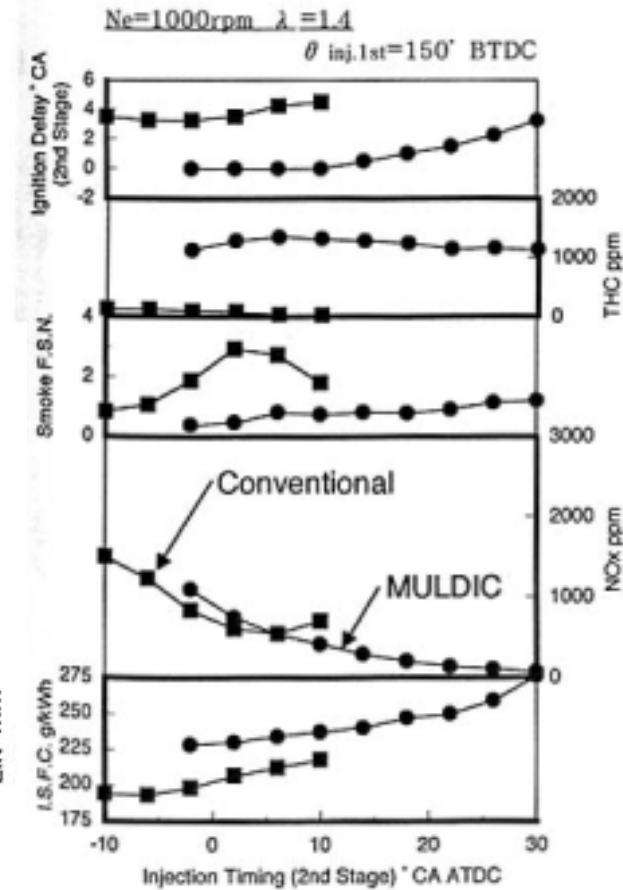
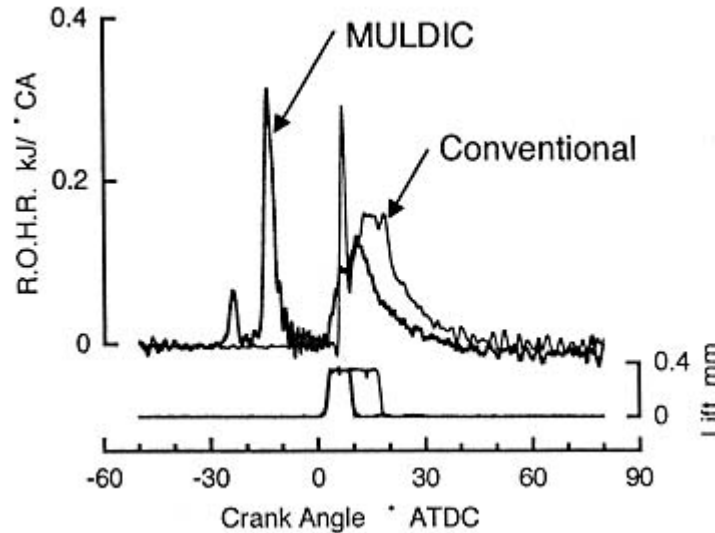
MULDIC

(Ref : SAE Paper 980505)

PREDIC achieved the simultaneous reduction of NO_x and smoke emissions. However, this technique can apply only to low and medium load condition. Therefore, **MULDIC was developed for NO_x reduction at higher load condition.**

MULTIPLE sTAGE DIESEL COMBUSTION :

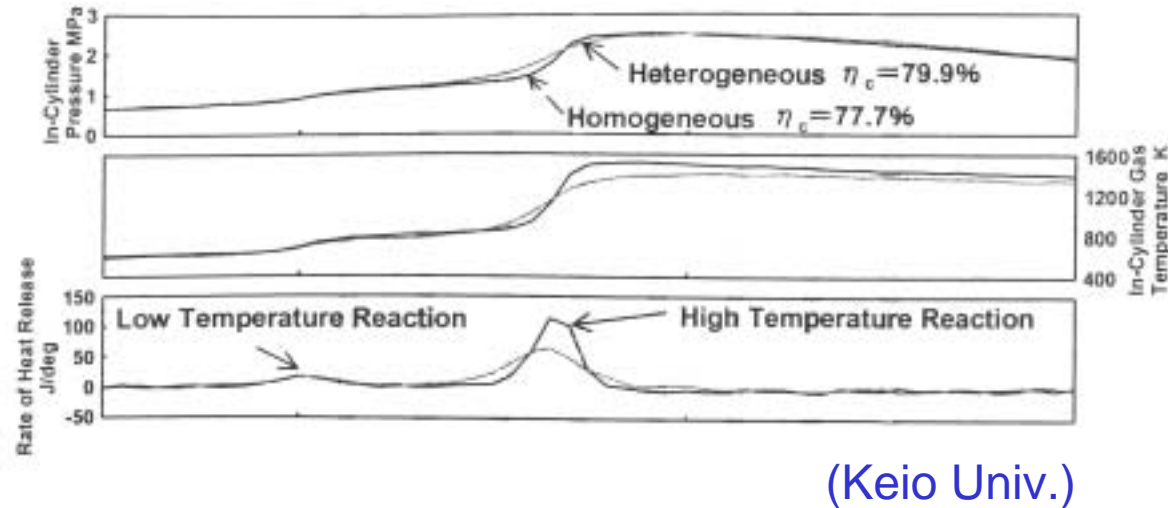
- **adopted a multiple stage injection method**
- can decrease NO_x and smoke emissions even at high load condition
- resulted in further improvement in exhaust emissions with EGR
- has trade-off correlation between NO_x emission and fuel consumption



R.O.H.R. of MULDIC **Emission characteristics of MULDIC**

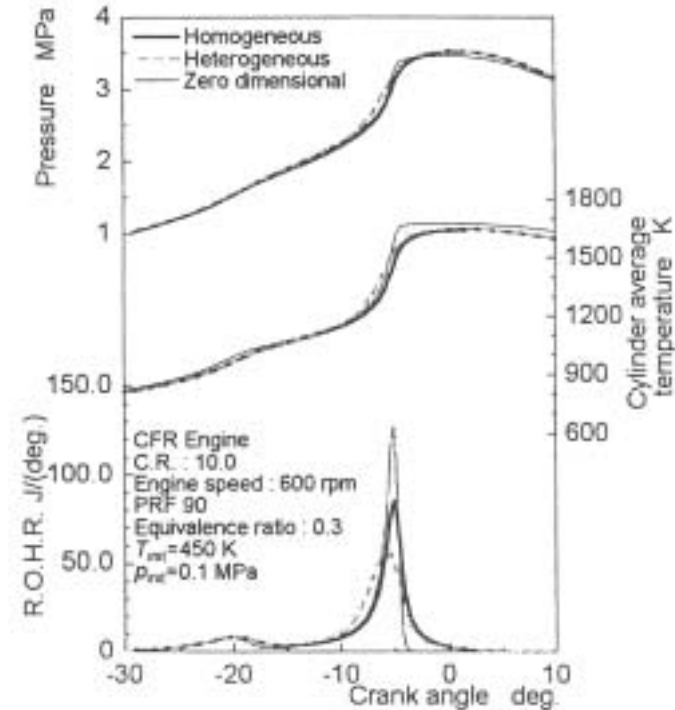
Heterogeneous Charge Compression Ignition (1)

Experiment



(Keio Univ.)

Calculation



(Ritsumeikan Univ.)

- **Heterogeneity of fuel distribution can achieve more moderate heat release rate.**

- Heterogeneous charge has a possibility to control the occurrence of main ignition.

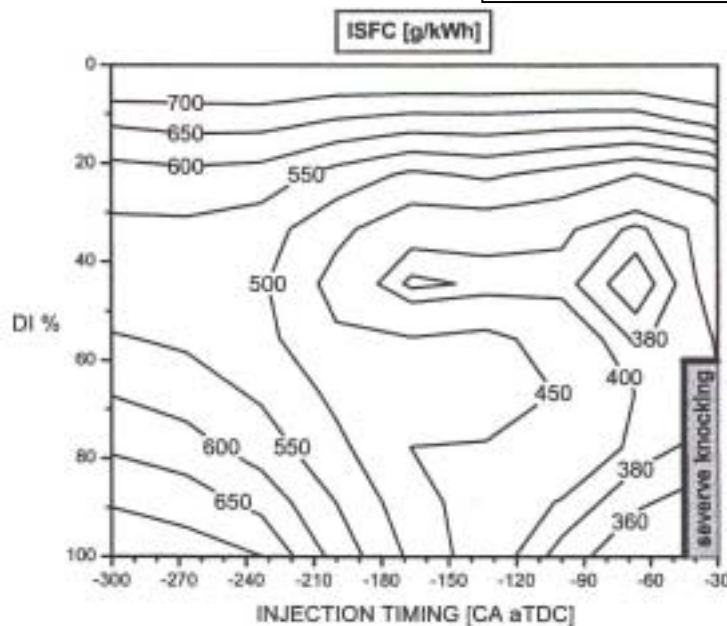
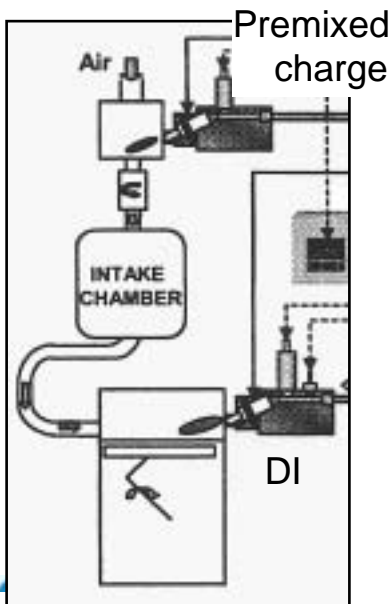
Heterogeneous Charge Compression Ignition (2)

(Ref : SAE Paper 2004-01-1756, Engine Research Center in U of W)

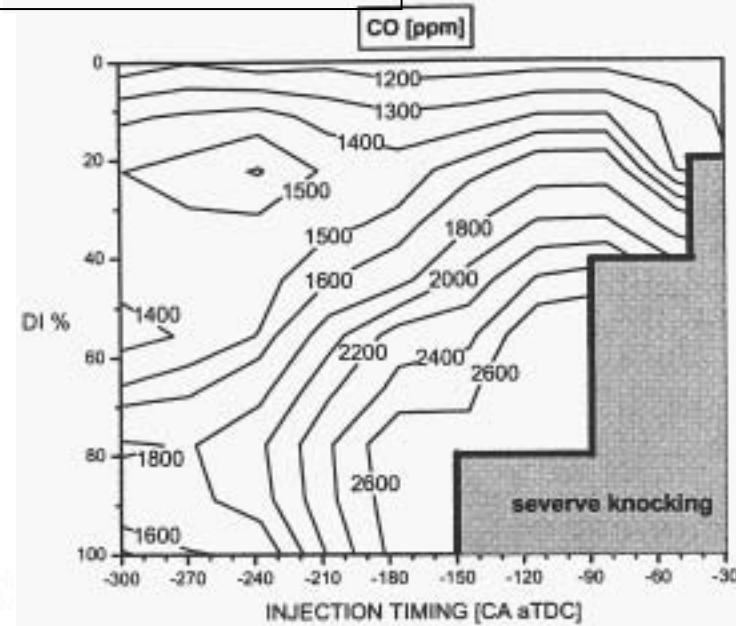
Stratification of the charge was varied 1) by retarding injection timing of DI.
 2) by altering the ratio of DI fuel to the total fuel.

- **Stratified charge shows potential as a viable enhancement for HCCI combustion at the lean limit.**
- At the rich limit, the stratification was limited by the high pressure-rise rate and high CO and NO_x emissions.

$$DI\% = \frac{\text{mass of direct injected fuel}}{\text{total mass of fuel in the charge}}$$



600rpm, $\phi=0.15$ (lean limit)



600rpm, $\phi=0.27$ (rich limit)

Fuel supply system

II Borderless in Gasoline Eng. and Diesel Eng.



Fuel Design Approach Researches with Focusing Artificial Control of Spray Atomization and Evaporation

■ Use of Flash Boiling Spray → Artificial control of Spray Evaporation Process

■ Control of Spray Evaporation Process through Two Phase Region in Liquid – Vapor Equilibrium in Mixing Fuels

① Mixing Fuel of Liquefied CO₂ and n-Tridecane(gas oil)
→ simultaneous reduction both Soot and NO_x

② Mixing Fuel of Gas or Gasoline Component and Gas oil Component → control both evaporation and ignition

■ Future Study in Fuel Control

① Fuel Conversion by Sono-Chemistry

② Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamic

Modeling of Flash Boiling Spray

Nucleation process

$$N = 1.11 \times 10^{12} \exp(-5.28/\Delta T_0) \times \left\{ 10^{-4.34 \exp(-5t)} \right\}$$

Initial bubble diameter $2R_0$
 $2R_0 = 20\text{mm}$

Bubble growth process

$$R \frac{dR}{dt} + \frac{2}{3} R^2 = \frac{1}{r} (P_w - P_r)$$

and

$$P_w = P_v + \left(P_{ro} + \frac{2\sigma}{R_0} \right) \left(\frac{R_0}{R} \right)^{3n} - \frac{2\sigma}{R} - \frac{4\mu_1 R}{R} - \frac{4KR}{R^2}$$

Vapor formation process

(1) By cavitation bubbles growth

$$dM_{cb} = \frac{4}{3} \rho_v \pi N (R_{n+1}^3 - R_n^3)$$

(2) Owing to heat transfer

$$dM_{ht} = \frac{\alpha_{ht} (T_a - T_f') A \cdot dt}{h_{fg}}$$

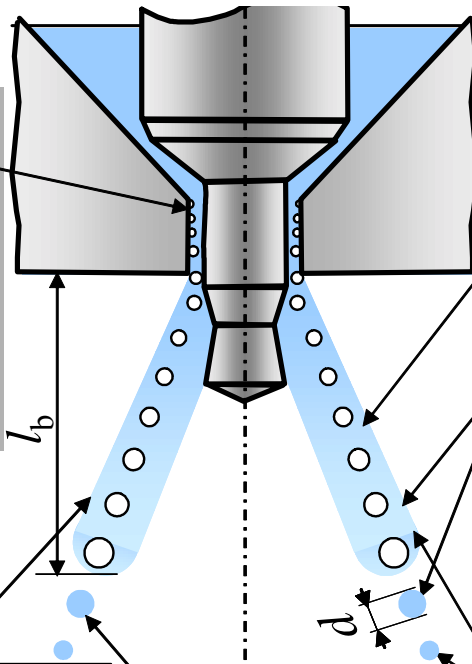
(3) By superheated degree

$$dM_{sh} = \frac{\alpha_{sh} (T_l'' - T_{st}) A \cdot dt}{h_{fg}}$$

Droplet formation process

$$\varepsilon = \frac{V_{bubble}}{V_{bubble} + V_{liquid}} \geq \varepsilon_{max}$$

Droplet number = $2 \times$ Bubble number

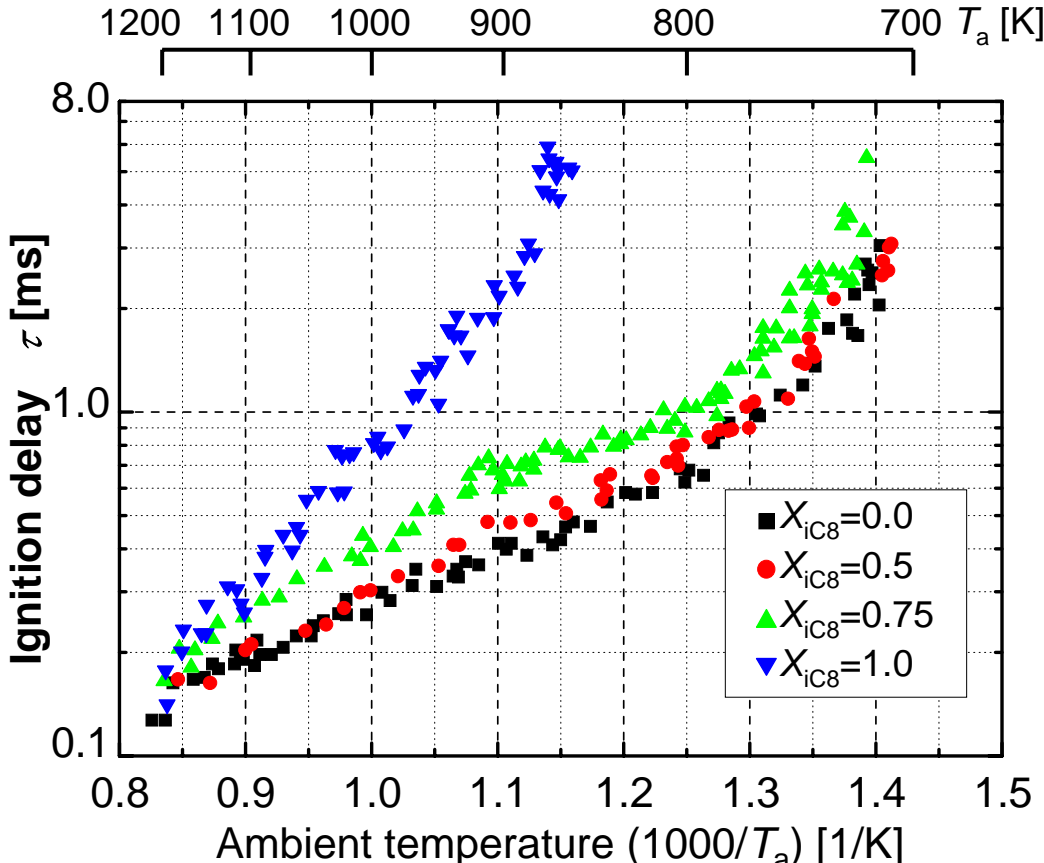
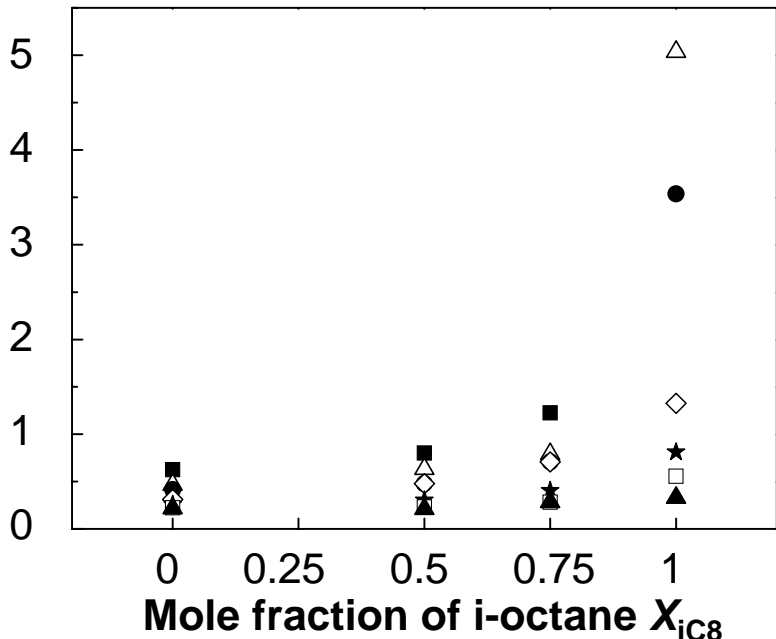


Ignition Delay of Mixing Fuel

of i-Octane & n-Tridecane (Experiments)

Ambient temperature

- 800K △ 850K ● 900K ◇ 950K
- ★ 1000K □ 1050K ▲ 1100K



Spray Evaporation Experiments in Mixing Fuel of n-Pentane & n-Tridecane

$n\text{-C}_5\text{H}_{12}$: boiling point 309.3 K
 $n\text{-C}_{13}\text{H}_{28}$: boiling point 508.7 K
 }
 $X_{\text{C}_5\text{H}_{12}}$: Mixing fraction of C_5H_{12}

Mixing Fuel and LIF Tracer

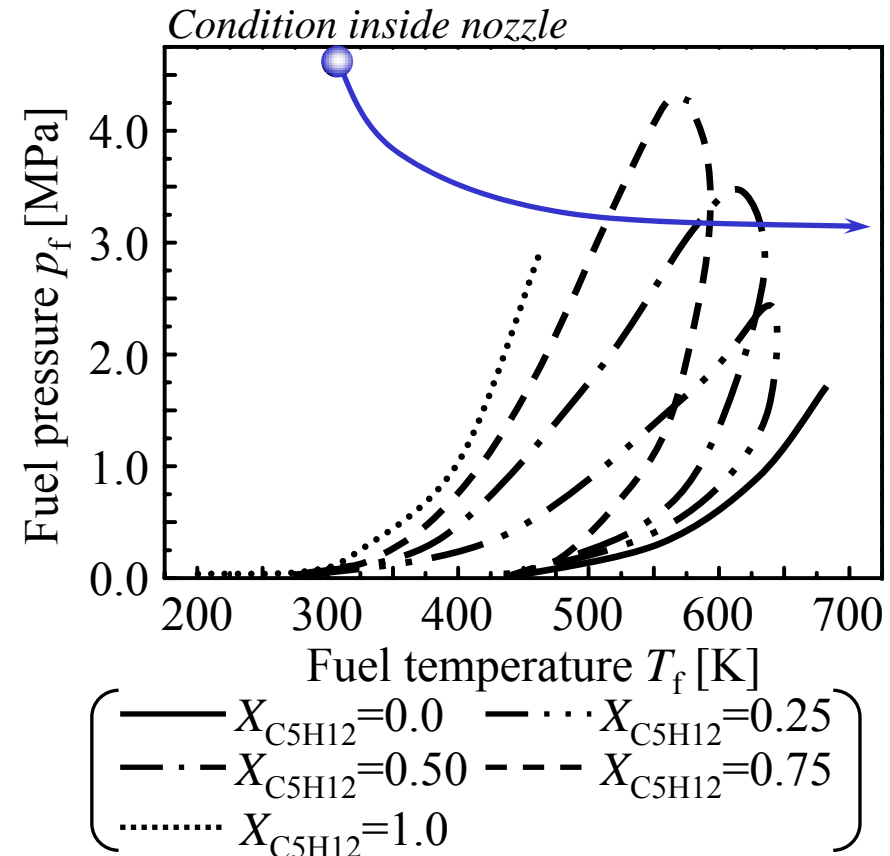
$X_{\text{C}_5\text{H}_{12}}$: Mole fraction of n-pentane
 $V_{\text{C}_5\text{H}_{12}}$: Volume fraction of n-pentane

$X_{\text{C}_5\text{H}_{12}}$	0.0	0.25	0.5	0.75	1.0
$V_{\text{C}_5\text{H}_{12}}$	0.0	0.14	0.32	0.59	1.0
Acetone [vol.%]	-	0.6	1.5	2.8	5
Tetraline [vol.%]	7	5.9	4.6	2.7	-

Acetone : C_5H_{12} Tracer

Tetraline : $\text{C}_{13}\text{H}_{28}$ Tracer

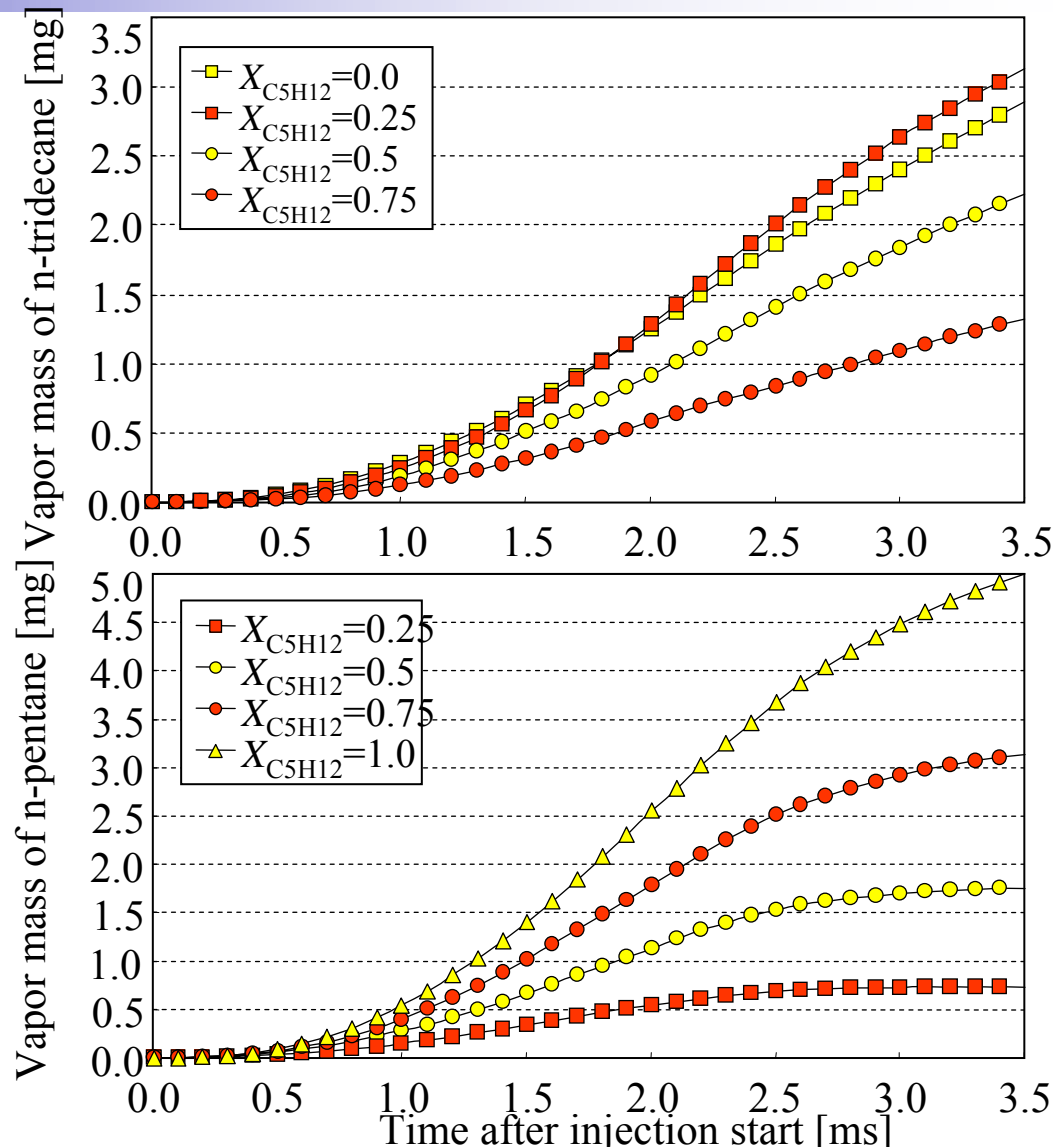
Two-Phase Region in P-T diagram



Temporal Changes in Vapor Mass for C5 & C13 Mixing Fuel KIVA Analysis

n-Pentane

n-Tridecane



Proposal on Fuel Design Approach Research

- (1) Physical Control = Capability of Time and Spatial Control on Fuel Vapor Distribution by Formation of Two Phase region in Mixing Fuel**
→ **Formation of Flash Boiling Spray → Improvement of Spray Evaporation**
- (2) Chemical Control = Capability of Control on Combustion Process**
→ **Emission Control – Soot & NO_x**
 Simultaneous reduction of both Soot and NO_x (CO₂-gas oil mixing fuel)
→ **Ignition Control (Gasoline-gas oil mixing fuel)**
→ **HC Control (Gasoline-gas oil mixing fuel)**
- (3) Improving Thermal Efficiency by Lower Injection Pressure**
→ **High Spray Atomization and Evaporation Quality with Flashing Process**
- (4) Control the Fuel Transportation Properties in Mixing Fuels**
- (5) Effective liquefaction of gaseous and solid fuels**
→ **Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics**



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→ **Optimization of specific heat, viscosity ,etc**
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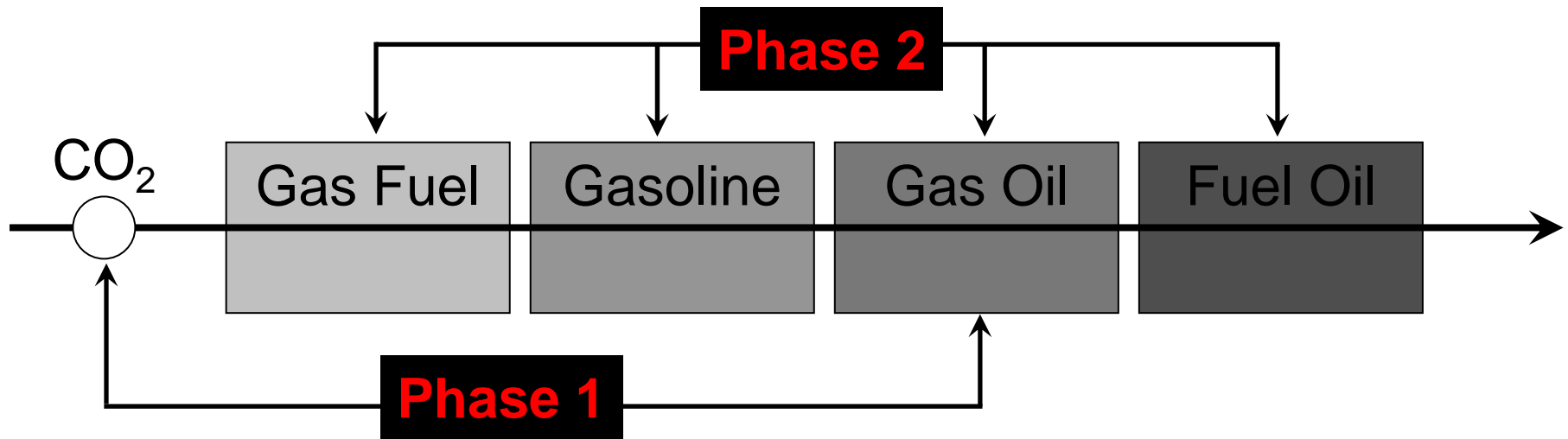


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Fuel Combination for Fuel Design



	High Volatility Fuel	Low Volatility Fuel
Phase 1	CO ₂	Gas Oil
Phase 2	Gasoline Gaseous Fuel	Gas Oil Fuel Oil

Chemical Thermodynamics and Two-Phase Region

Estimation of Two-Phase Region

P-T Diagram for Mixing Fuel with Liquefied CO₂ & n-tridecane

Expanded Corresponding State Principle

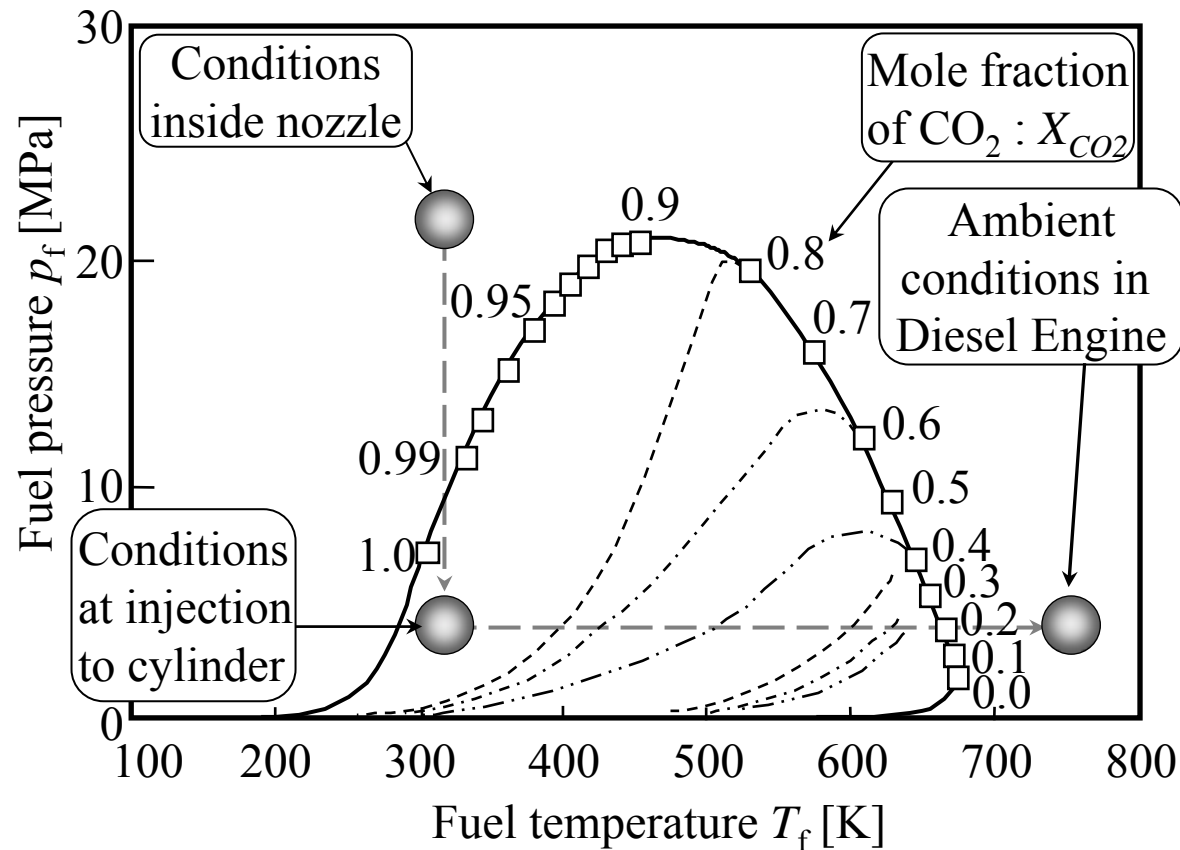
$$P_r = P / P_c, \quad T_r = T / T_c$$

Peng-Robinson Equation of States

$$P = \frac{RT}{V-b} - \frac{a(T)}{\{V(V+b)+b(V-b)\}}$$

Fugacity of Liquid & Gas

$$\phi_i^G = f_i^G / (y_i \cdot P), \quad \phi_i^L = f_i^L / (X_i \cdot P)$$

$$f_i^G = f_i^L$$


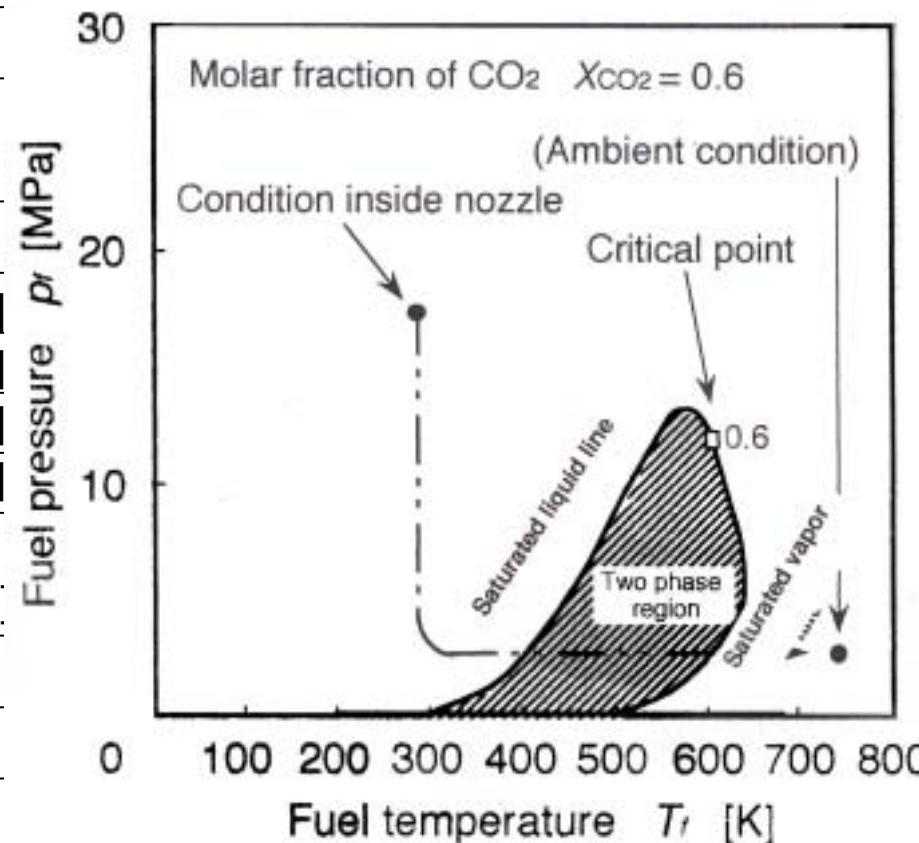
The prediction of Two-Phase Region

Combustion Experiments in CO₂ & n-Tridecane Mixing Fuel

Experimental conditions

Equivalent crank speed	200 [rpm]	
Water jacket temperature	353 [K]	
Compression ratio	15	
Injection nozzle dimension	$dn=0.18$ [mm] $ln/dn=4.17$	
Injection pressure	16 [MPa]	
Injection quantity (n-tridecane + CO ₂)	$X_{CO_2}=0.0$	10.0 + 0.0 [mg]
	$X_{CO_2}=0.4$	10.0 + 1.6 [mg]
	$X_{CO_2}=0.6$	10.0 + 3.6 [mg]
	$X_{CO_2}=0.8$	10.0 + 9.5 [mg]
Injection timing	5.0 ± 0.5 [deg.CA.BTDC]	
Excess-air ratio	25	
Ambient temperature at injection	750 [K]	
Ambient pressure at injection	3.2 [MPa]	
Initial cylinder pressure	0.1 [MPa]	

P-T Diagram for Mixed Fuel in RCEM



Combustion Experiments – Conditions and P-T diagram for LPG & C₁₃ Mixing Fuel with Fuel Temperature

Test fuel

LPG + n-C₁₃H₂₈ (LPG/C13) $X_{LPG}=0.8$

Operating condition

Engine speed [rpm] 3600

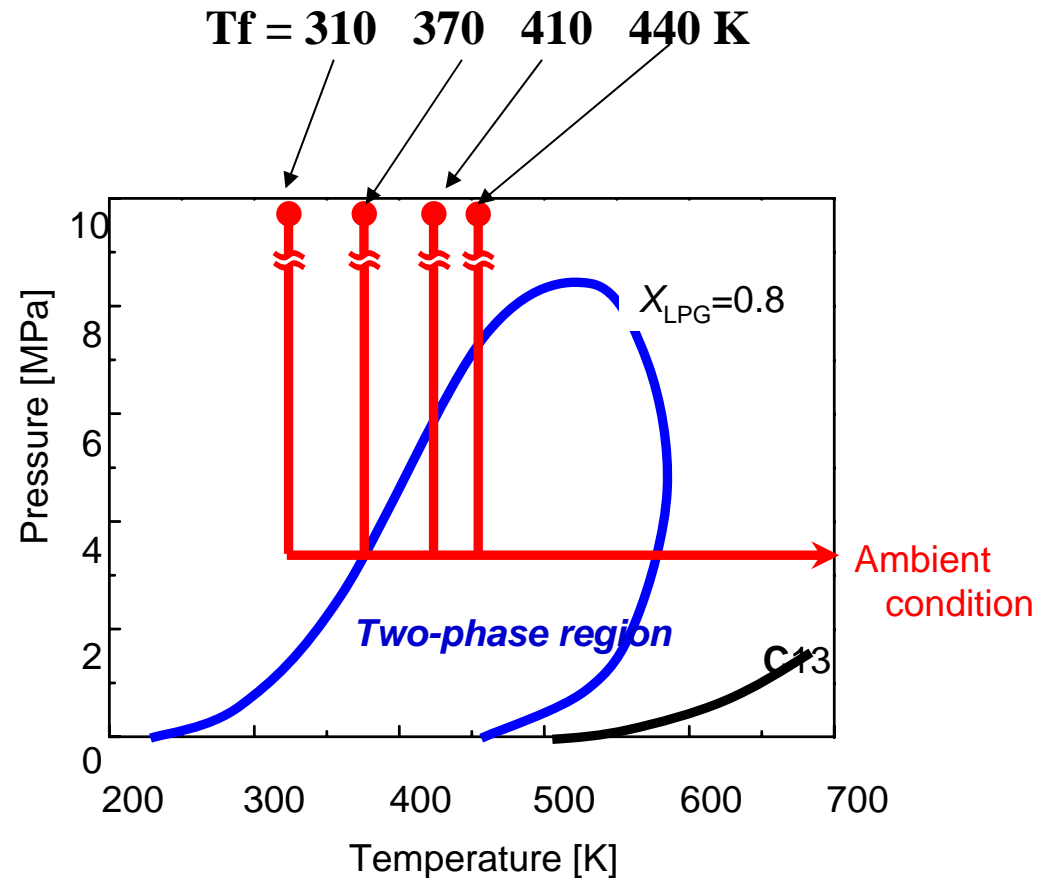
Engine load [%] 60

Injection condition

Injection nozzle (n-φ d) 4-φ 0.21

Injection pressure [MPa] 15MPa

Injection timing [deg.C.A.BTDC] 12.5



Finally,

**We are intending to couple Fuel Design Process
- Two Phase Region Profile -
with Combustion Chamber Geometry Design
considering Fuel Spray Evaporation Process**

**→ Artificial Control to optimize the Fuel Spray
Evaporation Process for each Engine Chambers**